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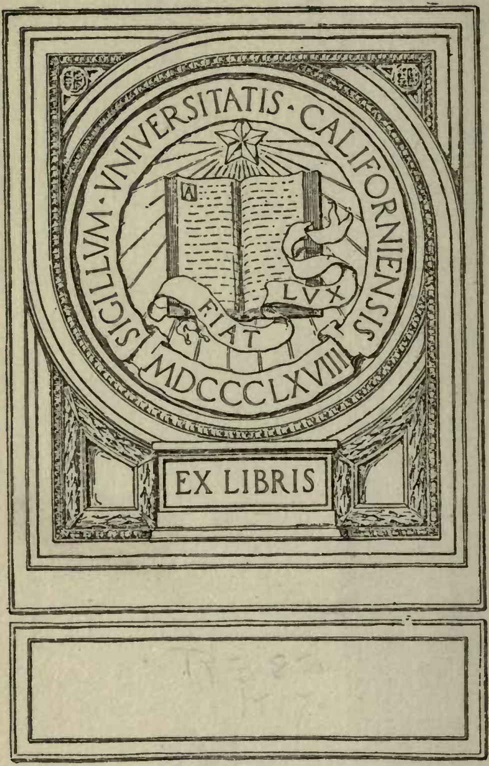
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ELECTRICITY

BY

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ELECTRICITY

CHAPTER I

ON FORCES ACTING THROUGH SPACE

THE conception of a force as something which pushes or pulls is familiar to every one. Equally familiar is the conception of an intervening link by which a force is transmitted from one body to another. If I pull a bucket of water out of a well the push exerted by the water on the bottom of the pail is transmitted to my hand by a very simple series of links. The bottom of the bucket pulls at its sides, these pull at the handle, the handle pulls the rope, and that finally pulls at my hand. We have here a transmission of force by links, all of which are in bodily contact. Thus far the process of transmission presents no difficulty to our conception of a force, but when we come to inquire why the water presses against the

bottom of the bucket, we have no complete answer. All we can say is that the push is due to the fact that the water is heavy. This means that the water in our bucket is attracted towards the earth, but what kind of intervening link there is which transmits a force from the earth to every particle of water and every particle of bucket and rope we are quite unable to say. Everyday experience has so familiarised us with the action of gravity that we have become accustomed to simply accepting it as a fact in nature, without further inquiry as to the machinery which is instrumental in the transmission of this force through the intervening space. We simply say that gravity is a force that acts at a distance, and since by direct experiment and astronomical observation it has been found possible to formulate a mathematical expression for this force, there is, from a purely practical point of view, no need to find an explanation of the machinery by which this force is transmitted through space, whether the space be quite empty or filled with other bodies.

The confession of ignorance as to the nature of this machinery of transmission is, however, not a denial that such machinery exists; on the contrary, the conception that

physical action can take place without the intervention of physical causes is repugnant to the human mind, and therefore physicists have invented the ether. By this they mean a physical something which pervades all space, whether filled by bodies or not, and this ether forms the connecting link by which forces are transmitted across space. Once we assume the existence of this physical though imponderable, that is, weightless substance, we may regard it as instrumental not only in the transmission of gravitational forces, but also of electric and magnetic forces and as the carrier of light and heat rays. There is, indeed, very strong experimental evidence that light, electricity, magnetism and all other manifestations of energy are propagated by ether vibrations. Maxwell was the first to point out that a connection of this kind exists, and by adopting his "electromagnetic theory of light" it can be proved mathematically, what has also been experimentally verified, that the speed at which a telegraph signal travels along the wire is equal to the speed of light propagation. It is extremely unlikely that such an agreement should be a mere coincidence, and we are therefore justified in assuming that the

ether, although originally invented to bridge a gap in our reasoning, has nevertheless a real existence.

The acceptance of the ether as the medium of propagation of all kinds of forces across space does not explain the mechanism of its action, but, by ascribing to the ether certain properties, we are able to express in concrete figures, by the use of any convenient system of measurement, the results of experimental investigation. The general law of action at a distance has been proved by direct experiment and by astronomical observation to be as follows: Let two active masses be concentrated in two points a certain distance apart; then the force acting between them, that is, the force which is being transmitted from one point to the other by the intervention of the ether, is proportional to the product of the two masses and inversely proportional to the square of their distance. In the case of gravity this force is always attractive, that is, tending to bring the masses nearer together; in the case of electricity or magnetism it may be attractive or repulsive according to the nature of the active masses.

It should be noted that the term "active mass" is merely conventional as far as

electricity or magnetism is concerned. It is not to be taken in its literal sense as applying to something which has bulk and weight. A steel bar, after being magnetised, weighs exactly the same as before, yet its ends exhibit certain properties which we may conventionally ascribe to accumulations of magnetic matter which, if brought near magnetic matter adhering to the end of some other magnetised bar, becomes "active matter" in the sense of producing either attraction or repulsion. The force is attractive if the ends of the bars brought near each other contain magnetic matter of opposite sign, and it is repulsive if the magnetism is of the same sign.

In the same way there is repulsion between two conductors both positively or both negatively electrified, and there is attraction if one is positively and the other negatively electrified. Also in this case electrification does not alter the weight of the conductor, although we may consider the electricity carried by the conductor as an "active mass" in the sense that the force of attraction or repulsion acting through space is due to it. In gravitation the force is always attractive, whilst with magnetism or electricity as active matter the force may be either attractive or

repulsive; in all cases, however, the same law applies as to the action through space.

The reader should note that the above statement of this law is no complete answer to the question as to the actual magnitude of the force. Experiment only teaches us that the force is *proportional* to the product of the two masses divided by the square of their distance, but if we wish to state the actual magnitude of this force in a definite figure we must agree on a system of units. As far as the attractive force between ponderable masses is concerned, such units are quite familiar; we know what is meant by the mass of a pound weight, and we also know how to measure a distance. With magnetic and electric forces the matter is not so simple. A distance we can measure in any length unit, but what about the unit for the "active mass"? We have seen that it is not a mass at all in the common acceptance of this term, and it can therefore not be expressed in any unit suitable for ponderable masses. We are thus compelled to settle the magnitude of the unit by the same formula which defines the force. The conception of unit active mass may then be derived from the following condition: If two equal masses one centimetre

apart act upon each other with unit force, then each of them is a unit of active mass.

The same definition of unit mass must also fit if applied to gravitational attraction, but there is a difference. We know from experimental evidence (T. Erismann, *Arch. d. Science*, Jan. 1911, pp. 36–45) that the attractive force of gravity is not in the least influenced by the medium which fills the intervening space. Two bodies in air attract each other with exactly the same force as in water; nor would the force be altered if we placed a wall between them. There would of course be an additional attraction between each body and the wall, but no additional force of the attraction between the bodies themselves.

With magnetic and electric forces it is different. If the force acting between two electrically charged bodies be measured, first in air and then when immersed in oil or separated by a wall of glass, we should find a decrease of force in the latter cases. In these cases the whole or part of the medium which at first was air has been replaced by some other substance with the result of an alteration in the force. We thus find that not only the magnitude of the charges and their distance, but also the

physical nature of the intervening medium has an influence on the force, and the mathematical formula expressing the magnitude of the force must take account of this. We must therefore introduce into the formula a coefficient, the numerical value of which will not only depend on the system of units chosen, but also on the medium filling the space through which the force acts. We thus arrive at the following mathematical expression—

$$F = f\,\frac{Mm}{D^2}$$

where M and m are the two masses, D is the distance and F is the force, all expressed in any system of units which may be convenient for the particular case in hand. The coefficient f will naturally depend on the magnitude of the units chosen; on their nature, that is, whether we deal with gravitational masses, electric charges or magnetism; and on the medium filling the space through which the force acts.

We do not know what electricity is any more than we know what magnetism is; all we know is that they are not of the nature of ponderable masses, and that under certain circumstances they may become the vehicle for the transmission of energy in a

similar manner to the ether itself. We might, in fact, consider them as ethereal manifestations without any attempt to explain the exact nature and mechanism of these manifestations. Such a conception is quite compatible with the practical use of our general formula; it simply means that we must look upon f as a kind of ethereal coefficient, the numerical value of which has to be found experimentally.

The conception of an ethereal coefficient, stated in this general way, is perhaps a little difficult to grasp. To make the matter clear I start by applying it to the familiar phenomenon of gravity, and then proceed to investigate the more unfamiliar phenomena of electric and magnetic forces. At the outset we must agree on the units we are going to use in giving a numerical expression to the attractive force between two bodies. If one of these bodies is the earth and the other a stone, this force is simply the weight of the stone. If the two bodies are the earth and the moon, the force is that which just balances the centrifugal force experienced by the moon in flying round in her orbit. The formula for the attraction given on p. 14 refers to masses concentrated in points, and it might

thus at first sight appear that its application to such a bulky object as our earth is not permissible. Neither moon nor earth can be considered infinitely small as compared to their distance. Nevertheless we may use the formula, for a mathematical investigation shows that in the case of spheres the summarised effects of all mass particles is the same as if the total mass were concentrated in the centre. Astronomy gives us all the data required for our calculation; all we need to get a definite numerical result is to agree on a definite system of units in which to express a force.

The definition of a mechanical force is: something which produces acceleration of a ponderable mass. Acceleration is the rate at which speed increases in respect of time. Thus, if an electric tramcar starting from rest attains its full speed of 24 miles per hour in the time of 20 seconds, its average acceleration is 1·2 miles per hour in each succeeding second, or "1·2 miles per hour per second." If instead of giving the speed in miles per hour we give it in metres per second, the acceleration of this car would be 0·535 metres per second per second. Taking the metre as the unit of length, the second as the unit of time, and the

kilogram as the unit of force, we have thereby also settled what the unit of mass must be.

A stone weighing one kilogram, and in fact any stone, when starting to fall from rest, acquires in the first second a velocity of 9·81 metres per second. Its acceleration or gain of speed is therefore 9·81 metres per second per second. Since the force which pulls the stone towards the earth is one kilogram, and since in any system of units the product of mass and acceleration represents force, the mass of our stone is the 9·81th part of unit mass. Therefore in the particular system of units chosen in this example, a stone weighing 9·81 kilograms has unit mass.

Expressing now the known masses of earth and moon in this system, and remembering that the average radius of the moon's orbit is 385,080 km., and the length of the month 27 days 7 hours 43 minutes, it is easy to calculate the centrifugal force from the well-known relation between mass, radius and time of revolution. The result is in round numbers 20,000 million million tons. It is difficult to grasp the meaning of so prodigious a force, but we may get an idea of its magnitude by calculating the diameter of a cylindrical bar of the strongest steel able to just support the

application of such a force longitudinally. It comes out at 320 miles in diameter. Having thus found the force, we can now determine the numerical value of the ethereal coefficient of mass attraction for the particular units chosen, namely, the metre as the unit of length, the kilogram as the unit of force, and a mass of 9·81 kilogram weight as the unit of mass. The result of this calculation is

$$f = \frac{6{\cdot}47}{10^{10}}$$

The symbol 10^{10} means that 10 is to be multiplied 10 times with itself. The numerical expression for f may also be written in the form

$$f = 6{\cdot}47 \times 10^{-10}$$

where the minus sign of the exponent signifies that 6·47 is not to be multiplied, but divided by 10^{10}.

In the above example showing how the ethereal coefficient may be determined for any arbitrary system of units, I have taken as the unit of mass the mass of 9·81 kg.; this was merely done as a matter of convenience, so as to be able to regard the kg. as the unit of force, as is customary in engineering. It is, however, more in consonance with first scientific principles not to fix arbitrarily a

unit for the force, but derive it from the three fundamental units of mass, length and time, since every physical quantity may be expressed by reference to these three units. If we choose the centimetre as the unit of length, the gram as the unit of mass and the second as the unit of time, we adopt what physicists call the centimetre-gram-second system of measurement. For this the abbreviated designation c.g.s. is customary. In this system force is a so-called derived unit, namely that force which, acting steadily in the same direction for a second on the mass of one gram, will give it an acceleration of one cm. per second per second. This unit is called the *dyne*, and from what has been said above it is obvious that 981 dynes go to one gram, or 981,000 dynes (approximately one million dynes) are equivalent to the kg. If we now repeat the calculation, using the c.g.s. system, we get the force in dynes if we express in the general formula

$$F = f \frac{Mm}{D^2}$$

the masses in grams and the distance in cm. The ethereal coefficient then has the value

$$f = 6{\cdot}6 \times 10^{-8}$$

The knowledge of this coefficient enables us to determine for any two bodies the attractive force if their masses, configuration and relative position are given. For spheres the calculation is quite simple, but for bodies of more complicated shape it is very difficult, and sometimes only possible in rough approximation. It would, for instance, hardly be possible to accurately calculate the mass attraction between two Dreadnoughts lying side by side, but by using the general formula and the coefficient f as here determined we get as a rough approximation a force of 7 lb.

It is, of course, out of the question to check such a calculation by direct experiment, since disturbing causes, such as the slightest breath of wind striking the side of the ship, will produce a disturbing force many times greater than the force to be measured. If, however, we could eliminate all disturbing forces, then a direct determination of f, quite independent of astronomical observation, would be possible. Such determinations have been made by Cavendish, Maskelyne, Airy and others, the most recent being Poynting's, carried out in the Birmingham University. Professor Poynting has measured, by means of an exceedingly delicate balance, the attractive

force between two lead spheres of known mass, and has thus determined f, and from this value he found the mass of the earth to be $6{\cdot}6 \times 10^{27}$ grams. In popular language, he has weighed the earth.

The reader may perhaps ask what all this has to do with electricity. Nothing directly. I have merely introduced the subject of gravitation, which is familiar to all, as a starting-point, so as to familiarise the reader with the conception of the ethereal coefficient; and I now go back to the consideration of electric and magnetic forces acting across space.

I assume that the reader is familiar with the usual textbook explanation of how bodies may be electrified, or, as it is also termed, charged with electricity. Imagine then that we have given electric charges to two spheres which are suspended from silk threads. Such suspension is necessary, for if we were to handle the spheres or lay them on to the table their charges would leak away; if we wish a body to preserve its charge for a sensible time we must support it by an insulator—such as silk, glass, mica, ebonite, which does not allow electricity to flow along or through it. Metals offer a very easy path for the flow of electricity, and are therefore called conductors.

There is no sharp line of demarcation between insulators and conductors. Dry wood, for instance, is not a perfect insulator; and when damp it is not a perfect conductor. Dry air at atmospheric pressure is almost a perfect insulator, but if rarefied or at high temperature it becomes more or less of a conductor. All metals are conductors, but they are not all equally good conductors. Mercury is not so good a conductor as iron, iron is not so good as copper, and silver is still a slightly better conductor than copper. The difference between the two last-named metals is, however, not great enough to justify commercially the use of silver instead of copper wire in the construction of electrical machinery. For the present we need not inquire further into any fine gradations between conductors and insulators.

We assume that the silk threads used for the suspension of the charged spheres and the air surrounding them are perfect insulators, so that the spheres will retain their charges as long as they do not come into actual contact with each other or some other conductor. If we suspend the spheres near each other we find that they do not hang plumb. If they are both positively or both negatively charged the distance between

their centres will be greater than the distance between the points of suspension. If the charges are of opposite sign, the opposite will be the case. This shows respectively that a repulsive force and an attractive force is causing the deviation from the vertical. If we know the weight of the spheres, measure their distance and the angle of deviation of the suspending threads from the vertical, the force acting between the two charges can be calculated from well-known mechanical principles in quite a simple manner.

It is, however, necessary to avoid disturbing influences. The spheres must hang in the middle of a very large room, so that floor, ceiling and walls are far removed, and we must make the observations by telescope, as otherwise the presence of the body of the observer near the spheres would disturb the electrical equilibrium. I need hardly say that such an experiment would be expensive and difficult; in reality it need not be made, as there are other far more practical methods of investigation available, but it is convenient to imagine such an experiment, because it will enable me to explain in the simplest possible way certain first principles. Suppose then that we are not deterred by questions of

cost and have overcome all the technical difficulties. Let us first, without altering the amount of charge on each sphere, merely shift their positions so as to get different distances. Measuring the force in each case, we will find that this force varies inversely as the square of the distance. We have thus verified part of our general equation. Now let us retain one particular distance and change the amount of charge, first on one sphere only and then on both. We find that the force varies directly as the product of the two charges. This experiment confirms the rest of the equation.

Writing now Q and q for the quantity of charge on each sphere the general equation takes the form

$$F = f\frac{Qq}{D^2}$$

In the case of both spheres containing equal charges this may also be written as an equation between the product of F and D^2 on the one hand, and f and Q^2 on the other—

$$F \times D^2 = f \times Q^2$$

Suppose we have succeeded in so adjusting the charges that $F \times D^2$ is unity; this might be the case for $D = 10$ cm. and $F = \frac{1}{100}$ dyne,

or D = 1 cm. and F = 1 dyne. The product $f \times Q^2$ will then also be unity. All that our experiment tells us is that the product of two things is unity, but it does not tell us the separate value of each of the two things, which is only another way of saying that we do not know and probably shall never know what electricity really is any more than we can know the real nature and value of the ethereal coefficient. We can, however, choose one of the factors, and then the other is also determined. If we adopt the definition of unit mass given on p. 13, then Q is 1 and Q^2 is also 1. From this it follows that f is also 1, and our general formula simplifies to

$$F = \frac{Qq}{D^2}$$

In adopting this formula we have arbitrarily settled the magnitude of the unit of electric quantity. It is such a quantity of charge as will give the force of one dyne, if acting on an equal charge at a distance of one cm.

It will be noticed that the train of reasoning followed here is different from that we followed in the case of gravitation. There we started by adopting a particular quantity of ponderable matter as the unit, namely the gram. This is the obvious way, because we know

what the mass of a gram is and we can reproduce it at any time. A cubic cm. of water at four degrees C. has the mass of one gram. Having thus settled the magnitude of the mass unit we determined the numerical value of the ethereal coefficient. In the electrical case we settle arbitrarily the value of the ethereal coefficient as unity, and determine on this basis the magnitude of unit electric quantity. In our experiment the spheres are at rest, there is no flow of electricity, and the system is in static equilibrium.

The unit of charge thus defined is therefore called the *electrostatic unit of electric quantity in the c.g.s. system.* In our experiment the room was filled with air. Let us now fill the room with oil. Since oil is an excellent insulator the spheres will retain their charges, but we shall observe a diminution of the force. The charge on each sphere has not altered, but the force acting between them has become smaller. We have settled the magnitude of unit quantity in such way that the coefficient f in air shall be unity, but after filling the room with oil we find that this coefficient is only say $\frac{1}{2}$. Whether it is exactly $\frac{1}{2}$ or some other fraction depends on the particular kind of oil used. To treat the matter quite

generally let us call the fraction $\frac{1}{K}$. The force will now be expressed by the formula

$$F = \frac{1}{K} \frac{Qq}{D^2}$$

K being a number depending on the medium in which the spheres are suspended. This numeric indicates the degree of attenuation of the force brought about by the presence of an insulating body between the spheres. This body, which separates the two electrified bodies, is called the *dielectric.* To bring back the force to its old value we must increase the charges. By using a dielectric we have enabled the spheres to hold a greater charge without exerting on each other a greater force. We have increased their capacity for storing a charge, and for this reason K is called the *specific inductive capacity of the medium,* or also the *dielectric constant* of the medium. The value of K is about 2 for oil, 2 to 3 for paper, 6 for mica, and may go up to as much as 10 for glass. The larger K, the greater is the charge with a given force pushing the electricity on to the conductor. This force must, however, not be confounded with the mechanical force of attraction or repulsion

with which we have been concerned hitherto; there is a relation between the two, as will be explained in Chapter III, but they are not identical.

The same reasoning as above applied to electric attraction and repulsion may also be applied to forces produced by magnetism, but if we attempt an experimental verification of the general law of forces acting through space we encounter some difficulty. When dealing with electricity it is quite easy to isolate a positive from a negative charge each on its own conductor, or, as we may also term it, it is possible to accumulate free electricity of one sign on a conductor. It is not possible to accumulate only north magnetic matter, or only south magnetic matter on one piece of steel. We always get magnetic matter of both signs simultaneously on the steel. If this has the form of a bar we can, by stroking it with a loadstone, make one end of the bar a north pole and the other a south pole, but if we break the bar in halves we do not get one half all north and the other all south. Each half again shows north at one end and south at the other. In experimenting on magnetic forces we are, therefore, always disturbed by the presence of magnetic

matter of the opposite polarity. Another difficulty lies in this, that the magnetic matter is spread over the whole of the bar—more dense at the ends, but still of sensible density at points towards the middle. Thus it becomes difficult to estimate the average distance of action. These difficulties are so great that the same methods of experimenting, which we supposed to be used when investigating electric forces, become quite impracticable, and other methods have to be devised.

These methods are based on the conception of the *magnetic moment*, that is, the product of the distance of poles into their strength. Any physical magnet can then be considered as a bundle of mathematical magnets, each carrying magnetic matter only at the extreme ends. We observe experimentally the summarised effect of all these elementary magnets, and by mathematical reasoning we are able to deduce the law under which magnetic forces act across space. Experiment shows that the law stated in the beginning of this chapter also holds good for magnetic forces. Moreover, the magnitude of the unit of magnetism may be determined in the same way. If we find that two equally strong poles placed one cm. apart exert on each

other a force of one dyne, then each contains unit of magnetic matter. This definition again means that we have arbitrarily assumed the ethereal coefficient of air to be unity.

When making the experiment with electric charges we found that by filling the space between the active charges with a substance such as oil or glass, the force was diminished. No such effect is observable with magnets. We may put them under oil or water, or we may put a sheet of glass between them, and we shall find precisely the same force. If, however, we immerse them in liquid oxygen there will be a decrease of force, and if such a thing as an iron atmosphere were possible, the decrease in such an atmosphere would be very great. We may therefore say that the ethereal coefficient for magnetic forces is unity for air, oil, wood and any so-called non-magnetic substance; and smaller than unity for magnetic substances such as iron, nickel and cobalt. If we try the experiment with a plate of bismuth we shall find a slight increase of the force, showing that the magnetic ethereal coefficient for bismuth is a shade greater than unity, the value assumed for air. For iron it is enormously smaller. We may say that iron is more permeable to

the transmission of magnetic forces than air or brass or wood, and the degree to which this transmission is facilitated is called the *magnetic permeability.* In physical and engineering calculation the permeability (which is nothing else than the reciprocal of the ethereal coefficient) is indicated by the Greek symbol μ, so that for magnetic forces the general equation for action over a distance D becomes

$$F = \frac{1}{\mu} \frac{Mm}{D^2}$$

The suitability of any particular kind of iron for use in electrical machinery depends on the value of μ, and the exact determination of this ethereal coefficient thus becomes a matter of practical importance. In making such determinations advantage is taken of certain relations which exist between electricity in the flowing state, commonly called electric currents, and magnetic effects. Since any flowing current represents energy, that is to say, is a dynamic phenomenon, such experiments have an electrodynamic character, and the unit of magnetic matter as defined above, under the arbitrary assumption that the magnetic ethereal coefficient for air is

unity, is called the *c.g.s. unit of magnetism in the electrodynamic system.*

We have thus two different systems of measurement, the electrostatic and the electrodynamic. They have been adopted as a matter of convenience in order to be able to regard in both the ethereal coefficient of air as unity. The result of this is that the absolute magnitude of electric quantity in the two systems is very different. In the electrostatic system unit quantity is exceedingly small as compared to the amount of electricity which goes to make up one unit of charge in the electrodynamic system. It requires 30,000 millions electrostatic units to make up one electrodynamic (or, as it is also called, *electromagnetic*) unit of electricity. The speed of light is 30,000 millions cm. per second. It is highly improbable that the agreement between the speed of light and the numerical ratio between the units should be a mere coincidence; but if it is not, then the ratio between the units is not merely a numeric but something which has a particular character, namely, the character of velocity, that is, a length divided by a time. Further, if we rule out the idea of a merely accidental agreement between two numbers, we are

driven to the conclusion that the ether is the actual carrier of force and energy; and this is the conception on which the modern science of electricity and magnetism, and in fact the whole structure of electrical engineering, is founded.

CHAPTER II

ON FRICTIONAL AND CONTACT ELECTRICITY

THE distinction generally found in text-books on physics between the so-called "frictional" and "contact" electricity does not imply that there are two different kinds of electricity, but it refers to two different methods of producing electrification of bodies. Besides these two there are other methods, and some of them are of much greater practical importance. Those will be discussed in subsequent chapters; for the present we restrict the discussion to the two methods mentioned above.

The term "frictional electricity" indicates the process by which the electrification of a body is produced. If a stick of sealing-wax is rubbed with a flannel, both these bodies show electrification, but of opposite sign. We agree to call the electricity residing on the sealing-wax negative, and that on the flannel positive. Electricity may also be

produced by rubbing a glass rod with a pad of leather, which has been covered with a mercury amalgam of zinc. In this case the glass rod shows positive electrification, and the pad negative. The old physics text-books, therefore, also speak of a "vitreous" and a "resinous" electricity, meaning thereby respectively electric charges of positive and negative sign. The electrification is the result of friction between two different substances, one becoming positively and the other negatively charged. Probably any pair of bodies can thus be electrified, provided the necessary care is taken to prevent the accumulated charge leaking off. The process is not even restricted to solids; the friction between a solid and a gas also produces electrification. This fact is utilised in the Armstrong electric machine, where jets of steam are caused to flow past the spikes of a metal comb. By the friction of the steam against the surface of the metal the latter becomes electrified. It is also well known that the friction of the gas escaping through the valve of a balloon produces electrification of the envelope, and under certain circumstances so strong an electrification that a spark discharge may occur. This danger is

avoided by the use of the ripping line on landing. The escape of gas then takes place through so large an opening that the velocity with which the gas passes the edges of the orifice is small, and the friction not sufficient to produce a sparking charge.

The friction between a pulley and its belt may in a dry atmosphere produce so strong a charge in the belt that sparks may be drawn from it. Such sparks are quite harmless to any person struck by them, but they may become a source of danger if inflammable substances are near. Thus in paper-making machinery, where the band of paper passes at high speed over hot metal rolls, it may become electrified to the extent of sparking and igniting itself. To avoid this danger it is necessary to fix spiked combs, which draw off the charge as soon as generated. In all these cases the electricity produced by friction is only an inconvenient by-product of some other operation; but if we wish to produce electricity for experimental work we may use special appliances based on the principle of electrification by friction. These are called "frictional machines." In substance they are nothing more than elaborations of the primitive glass rod and leather

pad, so that the friction may take place under a suitable pressure and with sufficient speed. The machine is also fitted with spiked combs for taking off the negative charge from the pad and the positive from the glass, and generally there is some contrivance added for storing the charges, or one of them. Machines of this kind are very inefficient, and as they have within our generation been superseded by much more efficient machines working on a different principle, which are treated in the fourth chapter, we need not discuss them in detail.

The frictional machine was, however, up to the year 1789 the only practical means of producing such electrification as the physicist of those days required for his experiments. In that year there came a change. L. Galvani, Professor at the Bologna University, found that electric effects could be produced in animal tissue, if this were put into contact with two different metals, in his case copper and iron. His experiment with the frogs' legs is so well known that it would be wasting space to describe it here. Galvani looked for the cause of the phenomena observed in the tissue and not in the metals. In this he was mistaken. He assumed the existence of

some mysterious " electric life force," and the name of " Galvanism " was given by the scientists of the time to this supposed force. This term has survived even to this day, though, except in some medical writings, rather in a metaphorical than a scientific sense.

Galvani's conception of an electric life force held the field for only a short time; it was proved to be a misconception by Alexander Volta, Professor at the Pavia University, who showed by a conclusive experiment that the cause of electrification does not reside in the animal tissue at all, but in the contact between the two different metals. He took discs of different metals, such as copper and iron or copper and zinc, and laid one on the other. The discs must be perfectly flat so as to present to each other even contact surfaces. Volta in his classic experiment found that such discs, if separated after having been in contact for ever so short a time, show signs of electrification; one being positively, the other negatively charged. In this experiment there is no question of any life force residing in animal tissue, for no such tissue is being used. The discs are simply laid one on the other, touched on

the back, and then separated. Volta recognised that the cause of electrification was the contact pure and simple between the two dissimilar metals, and for this reason we may speak of "contact electricity" or "voltaic electricity" when we mean the kind of electrification first discovered by Volta.

Various theories have been set up to explain what may be termed the mechanism of this electrification. According to Helmholz, the molecules of a metal are endowed with the ability to attract and hold both electricities, but not with equal force. These molecular forces are different in different metals, and in consequence of these differences there takes place an actual separation between the two electricities at the boundary surface between the two metals. Other scientists (notably De la Rive) doubt the existence of such a molecular force in the metal itself, and look for the cause of electrification in the influence of an intervening link between the two metals, namely, the moisture of the atmosphere. They point out that even with the most accurate ground surfaces it is obviously impossible to make molecular contact between the two metals; that there must always be interposed a film of gases and

vapours, and that it is by the intervention of this gaseous connecting link that the phenomenon called contact electricity takes place.

Whether the one set of theorists or the other have come near a true explanation, or whether both are mistaken, is not a matter which need concern us; the important fact is that electrification is produced by the contact between two metals, and that the intensity of their electrification, or the force by which the two electricities are separated across the boundary line of the two surfaces, does not depend on the extent of the surface of contact, but only on the quality of metals used in the combination. The force is greater with some combinations and smaller with others. By testing various combinations, it is thus possible to range all metals in a series, in which that metal which, combined with any other always shows a positive charge, stands at one end. This had already been done by Volta himself, who gave the series : ZINC—LEAD—TIN—IRON—COPPER—SILVER—GOLD. Zinc stands at the positive, and gold at the negative end of the series. This sequence has been verified by all later observers, who have also confirmed another

observation originally made and published by Volta, namely, that the electric force between any two metals in the series is equal to the sum of the electric forces between all intermediate pairs. Thus, if in any arbitrary scale the electric force between zinc and lead is 2, and that between lead and copper 5, then the electric force between zinc and copper is $2 + 5 = 7$.

The series given above ends with the most negative metal—gold; but Volta found that another substance, not a metal, but graphite, which is a special form of carbon, is still more negative than gold, and since Volta's time the series has been enlarged and extended by the addition of other metals and also sulphates and oxides, so that we must consider the phenomenon of electrification by contact to extend over a great variety of substances, and not to be restricted to a combination of metals.

Whether electrification is produced by friction or by contact, the process is in either case the separation of charges of electricity of opposite sign. We know that such charges attract each other, and that if accumulated on conductors sufficiently near, the conductors themselves will experience an attracting force.

The tendency will be to bring the conductors together, and if they are held firmly in place, the tendency will be for the charges themselves to leave the conductors and unite. Whether they will actually do this depends on the distance between the nearest points of the conductors and the strength of the charges accumulated on them. Under certain conditions the force of attraction may be sufficiently great and the distance sufficiently small to cause electricity to leap across the intervening space, and then we have the familiar phenomenon of an electric spark.

The same phenomenon is observed in lightning, in which case the conductors may be two clouds charged with electricity, or a cloud and the earth. The force which in an electric machine causes the separation between positive and negative electricity is called the "*electromotive force*," and the practical unit in which the magnitude of electromotive force is expressed is called the "volt." To give the reader an idea of the size of this unit it may be mentioned that the electromotive force (or e.m.f.) with which electricity is caused to flow through an incandescent lamp is of the order of 100 to

250 volts, according to the type of lamp used. The most prevalent voltage employed for domestic lighting is 220 v. In comparison with this the e.m.f. of contact is very small, and that produced in a frictional machine is prodigiously large. The latter may easily reach tens of thousands or even hundreds of thousands of volts, whilst the e.m.f., under which lightning flashes occur, may be many millions of volts. Between the process of producing electrification by friction and producing it by contact, there is thus an enormous difference in degree, but no difference in kind, both processes being simply directed to the separation and isolation of charges of different sign.

If the positive and negative conductors of a frictional machine are connected by a wire, the charges rush along this wire to equalise each other, leaving both conductors without charge. We may imagine a simultaneous movement of positive and negative electricity along this wire in opposite directions, or we may imagine only the positive charge flowing along the wire in the direction of the negative conductor and spreading itself over its surface, and thereby neutralising the negative charge previously accumulated on it. What pre-

cisely takes place we do not know, but as a matter of convenience we assume that there is only one current, namely, that which flows from the positive to the negative conductor, much in the same way as water will always flow from the higher to the lower level.

Electricity, being an imponderable entity (in reality merely a form of energy), cannot be connected mentally with any conception of level, such as is legitimate in the study of the movement of heavy bodies. Nevertheless it is convenient to introduce a somewhat analogous conception to "high" and "low" when dealing with electrical problems, and this conception is that of "electric potential." Just as water tends to flow from the higher level to the lower level, so positive electricity has the tendency to flow from the conductor of higher to that of lower potential. The mechanical meaning of the term potential will be discussed in the following chapter; for the present it must suffice to note that as long as the two conductors are kept at a difference of potential by the working of the frictional machine, a current of electricity will flow from the positive to the negative conductor through the wire joining them.

The current obtainable from such a machine

is exceedingly small, and any attempt to produce the electric currents required for lighting or other technical purposes by the use of a frictional machine is foredoomed to failure. Where currents of any magnitude are required, we must use other methods of producing electricity. These will be discussed subsequently, but for the present it is important to note that, apart from a question of degree, the frictional machine is an apparatus whereby electric currents may be generated.

How does the matter stand with regard to electrification by contact between solid bodies? Can we thereby also produce an electric current? We have seen that two metals in contact electrify each other. Using copper and zinc, the former becomes negatively and the latter positively electrified; that is to say, the zinc becomes the body of higher and the copper that of lower potential, and at first sight it might appear that by joining the back of the zinc disc to the back of the copper disc by a wire, we should get a current flowing along this wire from zinc to copper. This is, however, not the case.

Whatever the material of the joining wire may be, it must fall somewhere into the

series of contact e.m.f., and be subjected to the law that the sum of its potential differences to zinc on the one side and to copper on the other side is equal to the potential difference between zinc and copper. We thus have a perfect balance of e.m.f.'s set up by the direct contact between the two discs and the indirect contact *via* the joining wire. Since the e.m.f.'s are in equilibrium, no current can flow. If it were possible to upset this equilibrium on one side or the other, then we could produce a current, and that is actually done by an arrangement of substances, some of which fall outside the series of contact e.m.f.'s. Such arrangements are called "voltaic cells." A familiar example is the so-called Leclanché cell (named after its inventor), which is found in almost every household for the working of electric bells.

Before entering on a study of voltaic cells it will be convenient to amplify the series on p. 40 by the definite statement of the e.m.f. to be obtained with any combination of the metals. The figures in the following table represent experimental results obtained by Ayrton and Perry, and recorded in Whetham's *Practical Electricity*—

Table of Contact E.M.F. in Volts

(Zinc is positive in relation to all the other substances given in this table.)

Substance.	Zinc.	Lead.	Tin.	Iron.	Copper.	Platinum.	Carbon.
Zinc . .	0	0·210	0·279	0·592	0·738	0·976	1·089
Lead . .	– 0·210	0	0·069	0·382	0·528	0·766	0·879
Tin . . .	– 0·279	– 0·069	0	0·313	0·459	0·697	0·810
Iron . .	– 0·592	– 0·382	– 0·313	0	0·146	0·384	0·497
Copper .	– 0·738	– 0·528	– 0·495	– 0·146	0	0·238	0·351
Platinum .	– 0·976	– 0·766	– 0·697	– 0·384	– 0·238	0	0·113
Carbon .	– 1·089	– 0·379	– 0·810	– 0·497	– 0·351	– 0·113	0

We have seen that no current due to contact e.m.f. can be produced in a circuit the members of which all belong to a series of contact e.m.f., and which therefore fall under the law that the potential difference between any two is equal to the sum of the potential differences of the intervening pairs. Whichever way we go round such a circuit the total e.m.f. is always zero. To get an e.m.f., and therefore a current in the circuit, we must find some conducting material which falls outside the series in the sense that it does not obey the law just stated. If the continuity of metallic contacts is interrupted by the interposition of such a material, then there will be no complete equilibrium, but a balance of e.m.f. in a definite direction and a current will result. Water is such a material; it

becomes strongly positive when in contact with any of the substances given in the table, but the difference of e.m.f. of the two combinations, water-zinc and water-copper, is not equal to that of the combination copper-zinc.

Assume for the moment that the difference is zero, or, in other words, that water

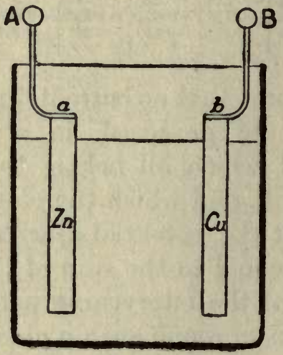

FIG. 1.

is quite inert as regards contact e.m.f. and simply acts as a conductor. This is not actually the case, but a convenient assumption for the purpose of explaining the way a cell may give an e.m.f. in an external circuit. Let, in Fig. 1, Zn and Cu be a zinc and copper plate respectively, and let to these plates be fastened strips of copper for the attachment of the terminals A and B. The plates are

not directly in contact, but are placed in a vessel filled with water. As we are only dealing with potential *differences*, we may arbitrarily fix the potential of one terminal at zero. Let this be the end of the copper strip soldered at *a* to the zinc plate. Then the potential of the zinc plate, which is due to the contact e.m.f. of the junction *a* where the copper strip is soldered to it, will by the table on p. 47 be 0·738 volts. Since by hypothesis the water is inert both as regards the zinc and the copper, this will also be the potential of the copper. The junction at *b* cannot alter this value, since at that place two equal metals are in contact. The potential at B is therefore also 0·738 volts, and on joining A with B by a wire a current will flow. Now let us replace the water by a dilute solution of sulphuric acid. The difference of contact e.m.f. of this liquid in relation to zinc on the one hand and copper on the other is about one-third of a volt, and this difference acts in the same sense as the contact e.m.f. at *a*. The result is that the potential of the copper plate, and therefore also of its terminal B, has now been increased to a little over one volt. Here we have a combination of substances, which, by virtue

of contact e.m.f., are causing a current to flow. In this primitive form the arrangement is, however, very imperfect.

As soon as the current flows, there come into play some secondary actions, which cause the contact e.m.f. between zinc and liquid, which is in a forward direction, to decrease, and that between liquid and copper, which is in a backward direction, to increase. The contact e.m.f. causes the current to flow, but as soon as the current flows, this current itself reduces the contact e.m.f. This reaction may be illustrated in a homely way by saying appetite causes a man to eat, but when eating he loses his appetite.

This interdependence between cause and effect is observable in all physical processes, and in its bearing upon the relation between electric currents and mechanical forces it has been formulated by Lenz, and is known as Lenz's law. Here we have to do not with mechanical, but with chemical forces. The current, in passing through the liquid, decomposes it, sending oxygen to the zinc, which is dissolved, and hydrogen to the copper, where it forms a coating and introduces an additional counter e.m.f. of contact. This process is technically termed "polarisation".

of a cell, and the ingenuity of inventors has been and is even at the present day exercised in finding means to avoid or at least reduce the effect of polarisation.

The first and completely successful attempt in this direction has been made by Daniell, in 1836. He recognised that the cure for polarisation lay in preventing any hydrogen being liberated and carried to the copper plate. If the liquid in the immediate vicinity of the copper plate contained a copper salt, it would not be hydrogen molecules, but copper molecules that are precipitated on the copper plate, and this could, of course, not alter the original condition of the cell. He used, therefore, a solution of sulphate of copper as the liquid into which the copper plate is immersed. But now arises another difficulty. We must not let the copper sulphate come into contact with the zinc, for this would not give the desired e.m.f., and it would also, by reason of the dissolution of the zinc, very quickly spoil the solution. It is thus necessary to still use dilute sulphuric acid as the liquid into which the zinc is immersed, and at the same time anything like a mixing of the two liquids must be avoided. This object is attained by the employment of a porous pot

for the separation of the two liquids. The porous pot forms the inner vessel into which the acid and zinc are placed, whilst an outer vessel is provided for the reception of the copper plate, and the solution of copper sulphate. It is advisable to amalgamate the zinc with mercury so as to protect it against attack by the acid when the cell is not working. When it is working no protection is possible, for the electrochemical action must be going on as long as the current flows. By this action oxygen is carried to the zinc, and this is thereby dissolved, forming with the sulphuric acid zinc sulphate. Thus the electrical energy given by the cell to the external circuit is obtained at the cost of the chemical energy liberated in the oxydation of the zinc and its conversion into sulphate. The e.m.f. of the Daniell cell is quite constant; it is a little over one volt.

Since Daniell's time many types of depolarising cells have been invented, zinc being generally one of the metals employed. The current passes from the zinc through the liquid to the other plate, which may be of copper, as in the Daniell and Meidinger cell, or of platinum as in Grove's, or of carbon as in Bunsen's and others. Since the current

issues from the cell at the platinum or carbon plate, the terminal in connection with this plate is called the positive pole of the cell, the zinc terminal being the negative pole.

One of the most largely used types of cell with zinc-carbon electrodes is that designed by Leclanché. The liquid used in this cell is a dilute solution of salammonia, and the polarisation of the carbon is counteracted by the employment of a metallic oxide in contact with it. The carbon plate is placed into a porous pot and packed round tightly with a mixture of granular gas coke and manganese peroxide. This substance is a powerful oxydising agent; it gets hold of the molecules of hydrogen on their way to the carbon electrode, and thus prevents them settling there and causing a back e.m.f. of polarisation. This chemical action can, however, only go on at a moderate rate, so that the Leclanché cell is mostly used where weak and intermittent currents are required, as for instance, in the working of electric bells. If the cell is worked too hard, the chemical action, whereby polarisation is rendered innocuous, cannot keep pace with the rate at which hydrogen is carried to the carbon plate, and the e.m.f. of the cell, which under normal

conditions is about 1·4 volts, drops to a much smaller figure. If left standing idle a little while, the cell recovers and its e.m.f. rises again to 1·4 volts. It will be obvious that by joining up in the same sense a sufficient number of Daniell cells, or cells of any other type, any desired voltage may be obtained between the ends of the series of cells.

A special type of cell is the so called *accumulator* or *storage cell*, in which both electrodes are lead and some oxide of lead. This is a so-called *reversible* cell. On forcing a current through in one direction, the oxide on the plate where the current enters the electrolyte (dilute sulphuric acid) is reduced, and the other electrode becomes more highly oxidised. Thus the cell is *charged*. If then the cell is connected to any working circuit, it gives a current in the reverse direction; the previously strongly oxidised electrode being reduced and the other becoming more oxidised, the cell *discharges*. These lead accumulator cells are made up into *storage batteries*, which are extensively used in electricity works.

CHAPTER III

ON POTENTIAL

In the first chapter we investigated in a general way the force acting between two bodies, and we found that this force may be expressed by a mathematical formula which is the same for real masses, electricity and magnetism. The units as regards length, time and force may be the same in all cases, but the units in which we express the amount of active matter producing the force must naturally be different in each case. We have also seen that the nature of the medium across which the force acts is immaterial in the case of gravitation, but may modify the force in the case of electricity and magnetism. Let us now, without for the moment specifying any particular kind of active matter, assume that one of the bodies contains a large amount of active matter, say M units, and that the other contains one unit only. For brevity I shall call them the large and the small body. We can then use the small body to in-

vestigate the properties of the space surrounding the large body. In this investigation the only variables are the force and the distance from the active centre of M, the force being always directed either towards or from that point.

The force may thus be considered as an attribute of space, and it becomes possible, even if M itself is inaccessible, to determine its magnitude and location by measuring the direction and magnitude of the force experienced by unit matter in different parts of space. It is not even necessary that the measurements should be made on unity of active matter; any convenient quantity of active matter in the small body will serve. All we need do is to reduce the measured force in the ratio of the actual amount of active matter used to its unit value. It is in this manner that astronomers, by observing disturbances in the orbit of a known star, can predict the existence of some heavenly body not yet discovered by the telescope. The astronomical problem is exceedingly complicated because of disturbances from other active masses for which allowance has to be made, but in studying the same problem as applied to electric charges no such complication need

arise. We can so devise the conditions of the experiment that no other force than that acting between the large and the small body is present. The condition that one body should contain a charge large in comparison with the other is not essential, only convenient, as it obviates the necessity of making mathematical corrections which would be necessary if the small body contained a charge of the same order of magnitude. In this case the assumption that the charge distributed over the surface of a sphere acts in the same way as if it were concentrated in the centre is no longer strictly true for small distances, so that certain corrections become necessary.

The first physicist who investigated quantitatively the action of electric and magnetic forces across space was Coulomb, who towards the end of the eighteenth century invented for this purpose an instrument known as the torsion balance. As applied to electric measurements, it consists essentially of a very light scale beam made of sealing-wax and glass fibres, and suspended horizontally from a thin wire attached to its middle. One end of the beam carries a gilded pith ball, and the other a mica disc as a counterweight. The

beam cannot dip either way, but it can be set into different angular positions by giving a twist to the upper end of the suspending wire, or if the upper end of the wire is held in a suitable clamp, it may set itself into an angular position in accordance with any electric force acting on the pith ball. The wire is clamped in a so-called torsion head at the upper end of a glass tube. By means of the torsion head any desirable amount of twist can be given to the upper end of the wire and read off on a circular scale, whilst the angular position assumed by the beam is indicated on a second scale placed at the level of the beam. To protect the apparatus from air-currents the beam is enclosed in a cylindrical glass vessel. In making experiments with static charges it is important to minimise as far as possible dissipation of the charges through the air, and for this reason precaution should be taken to keep the air dry. This is done by placing into the glass vessel a saucer with chlorate of potassium. Any moisture originally in the air is thereby extracted and rendered harmless. The cover of the vessel has an aperture through which is lowered a second gilded pith ball so as just to touch that on the scale beam.

If now an electric charge is imparted to the two balls by touching the connecting wire of the fixed ball with a charged body, the beam is deflected, and the deflecting force can be calculated from the angular position at which the beam comes to rest. By twisting the torsion head the balls can be brought nearer, and a new position of equilibrium obtained. Observations of the deflection, with different amounts of twist of the torsion head, are taken, and from these it is possible to calibrate the balance, that is, mark out the scale, and then use the calibration for the exact measurement of the repulsive forces acting between the balls. Coulomb was thus able, by means of his torsion balance, to establish the law of electric action at a distance.

We may look on the torsion balance as the practical way of making the experiment described in Chapter I. There is, however, this difference. The purely experimental part of the work with the torsion balance is quite simple, and free from external disturbing influences, but the mathematical investigation of the experimental results is complicated. On the other hand, the mathematics of the experiment described in Chapter I are quite simple and elementary, but the practical carry-

ing out of such an experiment would be very difficult and costly. As I am, however, not concerned with any actual experiment, but with the explanation of first principles, I prefer to base this explanation on the mathematically simple but technically impracticable experiment rather than on an experiment which, although easy to perform, requires a complicated mathematical interpretation.

Let us then revert to the hypothetical experiment of a large electrified sphere suspended by a silk thread in the middle of a large room. Let the sphere contain a charge of Q electrostatic units of positive electricity. Let the small sphere contain unit positive charge, and let us assume that we may place this at, and measure accurately the force at, any point. We shall then find that the general law of action through space holds good if we measure distances between the centres of the spheres. This means that the distributed charge on each sphere acts as if it were concentrated in its centre, a fact which can also be proved mathematically, starting from the general law. The repelling force on unit charge is given in dynes by the expression

$$F = \frac{Q}{D^2}$$

This force diminishes rapidly as we increase the distance; at 10 times the distance it is $\frac{1}{100}$, at 100 times the distance it is $\frac{1}{10000}$ the original value. Obviously if the room is large enough it may be practically zero close to the wall, and yet quite sensible within a foot or so of the large sphere.

Let us assume that somehow or other we pick up a pith ball charged with unit positive electricity and carry it along any path to some point near the sphere. All the way we experience a repelling force, small at first, but rapidly increasing as we approach to the final position. In overcoming this repelling force we must impress mechanical energy on the pith ball, and the energy thus stored can again be recovered in letting the pith ball recede and perform mechanical work by overcoming some opposing force, so regulated that it balances at any point the repelling force of electricity.

We need not concern ourselves with the mechanism by which such a process could be carried out, since the whole experiment is only hypothetical and merely intended to illustrate principles. Our unit charge then is a carrier of energy, or a means of storing energy; and the amount of energy stored will depend on the charge on the sphere,

the medium in which the approach takes place, and the distance from the centre of the sphere at which the approach is arrested. Thus to every point of space surrounding the sphere corresponds a definite amount of energy. The nearer the point is to the surface of the sphere, the greater is the amount of energy required to bring unit charge to that point. By moving the pith ball nearer to the sphere we must expend energy, that is, store it; by allowing it to move farther away we obtain energy, that is, we diminish the amount stored. If we move the pith ball round the sphere, taking care to keep at the same distance, we neither expend nor receive energy. In this case the movement takes place everywhere at right angles to the direction of the force, and consequently no work can be done. Our pith ball is only potent to give up energy if allowed to recede from the sphere in obedience to its repelling force, and the measure of this "potency," or, as we may shortly term it, the "potential," is a measure of the total energy which the pith ball yields if allowed to move from the point in question to a point so far away that the force has dwindled to zero—in mathematical language, to a point infinitely distant. The

potential has a definite value for every point of the space surrounding the charged sphere. We may thus define it: *The potential at any point of space is the energy required to bring unit positive charge from infinite distance to that point.*

We have yet to find a mathematical expression for the potential. To do so we shall assume the approach to the sphere to take place in a straight line. It is quite permissible to restrict the movement to this condition, for if the shape of the path made any difference to the energy expended on approach and recovered on recession, we should be able to construct a perpetual motion machine, as may be easily seen from the following consideration: Imagine that a path of approach could be found which required a smaller expenditure of energy than can be recovered if the pith ball is constrained to follow on its outward journey some other path, then we could by a suitable sequence of the two motions create energy. We know that the creation of energy is impossible, and we must therefore conclude that all paths are equivalent as far as the potential is concerned. We are thus justified to take that shape of path which lends itself most easily to a mathematical investigation, and that is the straight line.

Let us now subdivide the straight line, along which the movement takes place, into a very large number of little bits, each in itself so small that we may neglect any change of the repelling force within the two ends of this little bit. The force varies by a small amount from bit to bit, but within the limits of one bit or small step on the journey we consider it constant. Such a conception is quite permissible if we take the steps or elements of the path small enough. The energy corresponding to each elemental part of the journey is the product of the length of the element divided by the square of the distance to the centre of the sphere, and multiplied by the charge on it. To each step thus corresponds a little bit of the total energy, and by adding up all these little bits of energy we get the potential. It would be very laborious to actually map out the whole of the journey in this way and make the innumerable calculations here indicated. Fortunately there is no necessity for all this arithmetical work. By the application of a mathematical method known as the infinitesimal calculus we are able to arrive at the result in a very simple way by one operation. The result is

$$V = \frac{Q}{D}$$

where V is the potential in dyne-centimetres, Q the charge on the sphere in electrostatic units, and D the distance of the point from the centre of the sphere in centimetres at which the approaching motion has terminated.

The reader should note that the conception of a person actually carrying a body containing unit charge in his hand, and approaching it to the sphere, is merely introduced as illustrating a mathematical relation between certain quantities, and must in no ways be taken literally. The formula only says that the potential is an attribute of the particular point A in space distant D cm. from the centre of the active mass Q. In another point, A_1 distant D_1 cm., the potential will have a different value, say V_1. If A is nearer to the active centre than A_1, then V will be greater than V_1, and we may therefore speak of a potential difference $V-V_1$ existing between the points A and A_1. Or in symbols

$$V - V_1 = Q\left(\frac{1}{D} - \frac{1}{D_1}\right)$$

Since D is smaller than D_1, the potential difference is positive. We must expend energy in bringing the unit positive charge, and in fact any positive charge, from A_1 to A.

Conversely, the energy thus stored can be recovered if we allow the unit charge to recede from A to A_1, which it will do under the repelling force from the active mass Q. Positive electricity, then, tends to move from the point of higher to that of lower potential.

This is self-evident; but how does the matter stand if the sphere is charged with negative electricity? We have then not repulsion, but attraction of the unit charge. The force has changed sign. The potentials at A and A_1 are both negative, but that at A is more negative than that at A_1. Now by referring both to the same datum line we may also say the potential at A_1 is positive as compared to that at A. To make this matter clear, let me illustrate by substituting height for potential: On a tableland 2000 ft. above sea-level there is a mountain 500 ft. high. At the foot of the mountain a shaft is sunk 500 ft. deep. Referring vertical distances to the level of the plain we say the level of the mountain-top is +500 ft. and the level of the bottom of the mine-shaft is −500 ft.; but if we refer all heights to the sea-level we would give the mountain-top as +2500 ft. and the bottom of the shaft as +1500 ft.

Both levels (potentials) are positive, but the mountain is more positive than the mine.

Let us now revert to our positively charged sphere. At infinite distance the potential is zero, and as we approach the sphere it becomes positive and grows in value inversely as the distance diminishes. Its greatest possible value is at the least possible distance, which is on its surface. The maximum value, the potential of the sphere, is on its own surface, and is numerically given by

$$V = \frac{Q}{R}$$

where R denotes the radius of the sphere in cm. For a negatively charged sphere the potential at infinite distance is also zero, and on its surface it is

$$V = -\frac{Q}{R}$$

A unit charge free to move will therefore fly from infinity towards the sphere and right on to it. If the unit charge is carried on some conductor having ponderable mass, this conductor would strike the surface of the sphere with a certain velocity. It is easy to determine this, since we know the total energy (namely, the potential difference between in-

finity and the distance R), which, during the flight of this projectile, has been stored in it in the shape of kinetic energy. By a well-known law of mechanics the kinetic energy stored in a projectile is given by the product of half its mass and the square of the velocity. Since the mass and energy are known, the velocity can be calculated.

Let us apply, by way of illustration, this principle of equivalence between potential and kinetic energy to the calculation of the velocity with which a meteorite strikes our earth. The potential of gravity of the earth on a point on its surface is

$$V = \frac{fM}{R}$$

where M is the mass of the earth and R its radius. The energy stored in a meteorite of mass m is therefore

$$E = \frac{fMm}{R}$$

which may also be written in the form

$$E = \frac{fMm}{R^2}R$$

But $\frac{fMm}{R^2}$ is nothing else than the weight of the mass m, and we thus find that the

kinetic energy of the meteorite is the product of its weight multiplied by the radius of the earth. Adopting the engineer's unit of energy as the metre-kilogram, and the mass unit as that mass which weighs 9·81 kg., we must take the radius of the earth in metres, and shall get the velocity v in metres per second. Since the mass of our meteorite is supposed to be unity, we have the equation

$$E = 9{\cdot}81\mathrm{R}$$

from which we find $\frac{1}{2}v^2 = 9{\cdot}81 \times 636000$

$$v = 11150$$

The meteorite will strike the earth with a velocity of 11·15 kilometres a second; in reality a little less, because of the resistance of the air.

This digression has been inserted to show the application of the potential theory to a purely mechanical problem. Let us now return to the electrical aspect of this theory. We have a large sphere, charged with Q units of positive electricity, and suspended in the middle of a large room. The potential difference between any point of the wall and the surface of the sphere is numerically equal to the energy required to bring a unit of positive electricity from the wall to the

sphere. The wall of the room being in contact with the earth, both must be considered as at the same potential, and if we arbitrarily fix this as zero (which is evidently permissible since we deal with potential differences and may take our datum line where we like), then the energy expended is the absolute potential of the sphere. We may also now drop the conception of an immensely large room, and assume the sphere suspended in a room of any size, or even in the open. This does not mean that it will in all cases be equally easy to give the sphere the same charge Q irrespective of the surroundings; but it means that for the same charge Q the potential on the surface will be the same whatever the surroundings may be. Thus we may imagine the sphere charged in the room to the potential

$$V = \frac{Q}{R}$$

If now we knock down the walls, or carry the sphere into another room or into the open, there will be no change in its potential provided that we can avoid loss of charge by dispersion. Now how are we to give the charge Q to our sphere? We cannot pick

up positive units of electricity from the ground as if they were pebbles and carry them by hand to the sphere; we must proceed in a different way. Let us then take a frictional machine and connect its negative wire to the ground, and the positive to the sphere. If the machine is worked, it will push negative electricity into the ground and positive on to the sphere. In other words, a charging current will flow along that wire, and more and more electricity will accumulate on the sphere the longer the machine is at work. There is, however, a limit; beyond which the process of charging cannot go. At first, it is easy enough to push electricity on to the sphere, because there is only a little quantity there which repels the influx of new units, but as the charge proceeds the quantity accumulated grows, the potential grows, and it requires more and more energy to bring every single unit on to the sphere. Finally, a point is reached when the pushing force of the machine, or, as we term it technically, its electromotive force, is just able to balance the repelling force of the charge accumulated, but not able to add a single unit. Thus a state of equilibrium is reached, and the charging process has come to an end. If we want

to charge still a little more electricity on the sphere, we must increase the electromotive force, or e.m.f. of the machine, by working it quicker; this will again raise the potential, but a point must eventually be reached when e.m.f. and potential again balance.

We have thus, as the limiting condition of the process of charging, equality between potential and e.m.f. It may be objected that this statement cannot have any physical meaning, because we are comparing two things which by their nature are different. Potential is of the nature of energy, whereas e.m.f. is only one of the factors which make up energy. When we pay our electric light bill, we pay, really, for energy, and not for current by itself; nor do we pay for e.m.f. by itself; nor for the product of the two. What we pay for is the product of three things, namely, current, e.m.f. and time. The electricity metre, which says how much we have to pay, takes account of all three factors, and gives the energy as the product of amperes, volts, seconds, or, as a mere matter of convenience, it gives it in kilovoltampere hours, the unit legalised by Act of Parliament, and known as the "Board of Trade Unit" of electrical energy. As a matter of strict logic it is there-

fore not permissible to equate potential and e.m.f., but it becomes permissible as a numerical proposition the moment we adopt such a unit for the current, that the product of unit current and unit time equals unit charge in the same system as that adopted in expressing the charge on the sphere. Thus a current of i such units, flowing for t seconds, corresponds to a charge of q units. If the electromotive force required to push these q units on to the sphere is denoted by e units, then the energy expended is

$$e \times i \times t = eq$$

On the other hand, we know from the definition of the potential that the energy required to bring q units from the wall of the room to the sphere requires the energy V q; and hence it is evident that e and V are numerically equal. By adopting the system of units here explained, we are therefore justified in considering e.m.f. and potential as numerically equal, and can write

$$e = \frac{Q}{R} \qquad \text{or} \qquad Q = eR$$

The charge that can be accumulated on a sphere is the product of its radius and the e.m.f. developed by the electric machine. It has been pointed out that the conception

of a very large room, in which the sphere is suspended, is not necessary to our arguments. We may reduce the room to any extent, and still the definition of potential, or, as we now see, that of e.m.f., holds good. It is the energy required to carry unit positive charge from the wall to the sphere. Since there is no restriction to the size of the room, other than there must not be actual contact between wall and sphere, let the room shrink until it has become merely a spherical shell surrounding the sphere closely, the distance being a very small length δ. Let this be a mere clearance space, so small in comparison with the radius of the sphere that the repelling force of the charge Q on our unit has sensibly the same value at any point within this very narrow space. The repelling force is

$$\frac{Q}{R^2}$$

and since the product of force and distance traversed is energy, we find

$$e = Q\frac{\delta}{R^2}$$

and

$$Q = e\frac{R^2}{\delta}$$

instead of eR as found previously, when the

sphere was in a large room or in the open. Comparing now the two cases, namely, the sphere in the open and the sphere closely surrounded by a metallic envelope, it will be seen that to get the same charge on the spheres is not equally easy. The sphere hanging free requires the application of a much larger e.m.f. than the sphere within an envelope, or, to put it another way, the sphere with an envelope will, under the application of the same e.m.f., acquire a much greater charge than the sphere hanging free in space. The *capacity* of the sphere for taking a charge has been increased. This reasoning leads us to the conception of capacity as a property of the configuration of metallic bodies. We define capacity as the ratio of charge divided by e.m.f. Using the symbol C for capacity, the definition mathematically expressed is

$$C = \frac{Q}{e} \text{ and } Q = eC$$

Since we found previously that $Q = eR$, it follows that the capacity of a sphere in the open is given by the length of its radius expressed in cm. For the sphere with its envelope the capacity is

$$C = \frac{R^2}{\delta}$$

The ratio of the square of a length and a length is again a length, so that we have in both cases the capacity expressed as so many cm.

In deducing the conception of capacity we assumed that the conductor has a spherical shape, but obviously if, instead of suspending a sphere and charging it, we had suspended a metallic body of any shape and forced electricity on to it by the frictional machine, it would have acquired some charge proportional to the e.m.f. applied. The body of irregular shape also has capacity, only we may not always be able to calculate it exactly beforehand. It can, however, always be found experimentally. For this purpose we apply a known e.m.f. to charge the body and then discharge it through a special kind of measuring instrument. The instrument indicates the quantity of charge which has passed through it; and from the two measurements, namely, e.m.f. and quantity, we can determine the capacity. For certain shapes the determination of capacity, by mathematical reasoning, is quite easy. One case, namely that of the sphere, either free or in a shell, we have already treated. The case of concentric cylinders, or parallel cylinders, or a cylinder

and a parallel plane is also easily treated, but it would exceed the limits of this book to enter into such details, which have more immediate interest for the cable engineer or the telegraphist. The case of two parallel plates may, however, be here given, because the derivation of a mathematical expression for the capacity is exceedingly simple. We found that the capacity of concentric spheres is given by the expression

$$C = \frac{R^2}{\delta}$$

If we multiply nominator and denominator with 4π we do not alter the equation, so that we also may write

$$C = \frac{4\pi R^2}{4\pi\delta}$$

$4\pi R^2$ is nothing else than the surface of the sphere, so that we also have

$$C = \frac{S}{4\pi\delta}$$

The capacity is therefore given by the surface divided by $4\pi\delta$. The radius does no longer appear in our formula. If we assume the radius to be infinitely large, any part S of the surface becomes a plane, and we thus have for the capacity of two parallel plane surfaces

of S square cm., distant δ cm., the expression

$$C = \frac{S}{4\pi\delta}$$

which is again a length.

Bodies constructed for holding an electric charge, that is, intended to condense electricity on their surfaces, are technically termed *condensers*. The first condenser used by physicists was the so-called " Leyden Jar " accidentally discovered by Musschenbroek (1692-1761), Professor of Physics in Leyden, Holland. In the eighteenth century electricity was considered a " fluid," and Musschenbrock attempted to collect some of this fluid in a glass filled with water. He held the glass in the hand, and electrified the water by a wire placed in the glass and projecting sufficiently far out so that he could touch the conductor of his frictional machine with the wire. When removing the glass and taking out the wire, he received an electric shock much more violent than he could obtain from his machine directly. In this case the water formed the inner conductor and the hand the outer shell, whilst the space between the two was filled by glass.

This form of condenser has become known under the name of Leyden Jar, and is used to this day by physicists. It consists

of a glass jar coated on the inner and outer surface with tinfoil about half-way up. The uncoated part of the jar is varnished to minimise loss of charge along the surface of the glass. An improved form of Leyden jar has been designed by Mr. Mosicki, and is largely used in wireless telegraphy. The coating of tinfoil is replaced by silvering, and the shape of the glass vessel is designed with special reference to its ability to withstand very high e.m.f.'s. Whereas the ordinary jar of the physical laboratory can only be used with an e.m.f. of about 20,000 volts, the Mosicki condenser, as made for wireless telegraph stations, can be used up to an e.m.f. of 60,000 volts. Mosicki condensers are also used for the protection of electric power lines from atmospheric electricity, and from the effects of sudden electric disturbances. They act as a kind of electric buffer or elastic link, able to soften the blow which the line and machinery might otherwise receive with full force if there were, from any cause, a sudden increase in the charge on the system.

When the condenser is not subjected to a very high potential difference, the insulator separating its two surfaces or coatings need not be glass, but may be a cheaper material,

such as paraffined paper. The object of using some lining between the plates is twofold. In the first place it would be technically very difficult to insure a very small intervening space without the risk that the plates come actually into contact. If the condenser is not required to have a large capacity, and especially if it is to be used as a standard of capacity for comparison with other condensers, then the intervening space between the plates may be left without filling material. Such condensers are called "air condensers." Where a condenser of larger capacity is required as a standard, then the filling-in material, the so-called "dielectric," may be mica. This, even in thin sheets, is electrically very strong, and is also an excellent insulator. It is thus possible to make the space between the plates very small, and by this means obtain a larger capacity with a given plate surface than with an air condenser. The other reason for using another material than air as a dielectric is that the material by itself has the property of increasing the capacity.

We have seen in Chapter I that the attractive force depends on the medium between the two charged surfaces. If this medium is air, the force is greatest; if it is an insulator such

as oil, glass, mica or paper, it is K times smaller. This means that to bring a unit of positive charge to our sphere through such a medium takes K times less energy than to bring it through air. In other words, to obtain the same charge an e.m.f. K times smaller is sufficient, or, if the e.m.f. is the same, the resulting charge will be K times larger. Hence by using a dielectric other than air the capacity of our condenser is increased K times. The following table gives the value of K for some dielectric materials—

VALUES OF THE SPECIFIC INDUCTIVE CAPACITY K IN THE C.G.S. ELECTROSTATIC SYSTEM

Material	K
Glass	2–10
Mica	5–6
Insulating Oil used in transformers	2–1
Paraffin Wax	2·3
India Rubber	2·2–2·8
Gutta Percha	2·5–4
Paper, as used for power cables	2·6–3·5
Paper, as used in telephone cables	2–2·5
Paper, paraffined, as used in condensers	7·2
Distilled Water	76
Pure Alcohol	26

In the old method of making condensers with paper as a dielectric the coatings or "electrodes" were sheets of tinfoil, but in the modern type of condenser developed by Mr. Mansbridge, of the British Post Office, so-called metallised paper is used interleaved with plain paper, both being paraffined. The effect of this improvement is that the bulk, weight and cost of paper condensers have been reduced to less than one tenth of what they were formerly. The capacity of any condenser is given in electrostatic c.g.s. units by the formula

$$C = K \frac{S}{4\pi\delta}$$

This unit is inconveniently small, and for practical work a much larger unit, namely, the "microfarad," has been adopted. As the name implies, the microfarad is the one millionth part of the farad, and the magnitude of the farad is given by the following definition: A condenser of one farad capacity, when charged under the e.m.f. of one volt, will store that quantity of electricity which is represented by the flow of one ampere during one second. The ratio of the electrostatic unit of capacity to the microfarad is 1 to 9×10^5, so that the capacity of a

condenser expressed in microfarads is given by the formula

$$M = \frac{K}{113} \; \frac{S}{\delta}$$

where S is the surface of the dielectric in square metres, δ is the thickness of the dielectric in millimetres, and K has the value given in the above table.

In developing the theory of the potential we started with the experiment of bringing unit electricity from the wall of the room to a point outside the charged sphere; and, as a limiting condition, to its surface. Beyond that we did not go. But what happens if we pass the surface and carry our unit through to the inside ? A mathematical investigation shows that in this case no force at all is acting on the unit charge, and in fact on any body carrying a charge of any magnitude. Since in moving such a body about within the hollow sphere we experience no resisting force whatever, no energy is required to perform the motion, and consequently all points of the interior space must have the same potential. Any point of the inner surface of the sphere is a point in the interior, but since the surface has the potential $\frac{Q}{R}$ it follows

that this is also the potential right through the cavity of the hollow sphere. This law that the potential at any point inside a conductor is the same as the potential on its surface, may also be proved without the aid of mathematics by the following reasoning: Imagine a conductor of any shape, and assume it at first to be solid right through. No free electricity could possibly remain in the substance of the metal, since the mutual repulsion of all the elementary charges would cause these to try to move apart as far as they can. As the carrier of these charges is metallic, that is to say, offers no resistance to the free displacement or flow of electricity, there is nothing to hinder the movement, and consequently the charge will all accumulate on the outside surface. There is, therefore, no charge in the body of the metal, and we may, without changing the electrical condition, take away the inside and leave only the merest shell, and still there can be no electrical effect produced inside the shell. We may charge such a shell with the strongest machine made, and yet in the inside not a trace of electricity can be detected.

This has first been proved experimentally by Faraday, who constructed for the purpose

a large cage of wire gauze and went into it armed with the most delicate instrument for the detection of electric charges. The cage was placed on insulating supports and strongly electrified by a frictional machine. Not a trace of electrification could be detected in the interior or the inner surface of the wire gauze. The principle of the " Faraday Cage " has been applied as a protective device in various ways. Professor Artemieff, of the Moscow University, has constructed an electrical safety dress, which completely envelopes the wearer so that he is literally enclosed in a tight-fitting Faraday Cage. The dress is of metal gauze, and as long as the surface is continuous, the wearer is absolutely safe from shock. If a discharge flash from a high-tension apparatus should strike him, the charge flows through the dress to earth without doing any damage.

Another important application of the same principle is the protection of underground or submarine cables. The part of the cable that is below the ground or the sea is naturally protected against lightning strokes, but somewhere the end of the cable must be brought out to the surface of the earth and connected to some apparatus or machine. At that point both the end of the cable and the machinery

are liable to be struck and must be protected. The best possible protection is to place the whole of the machinery and the apparatus connected to the cable into an iron house. It is not necessary that the walls of the house be entirely made of iron. In Milan there is such a house for the protection of the junction of the overhead power lines coming from the Alps, and joining by means of certain apparatus with the underground cable network that supplies the town with electricity. In appearance this house is not different from any of the other factory buildings of the neighbourhood; nevertheless it is a Faraday Cage. The roof has an iron lining, the stanchions are well bonded with it and with each other, and go down to the moist subsoil. Below the plastering of the walls is a heavy expanded metal lining all connected to the roof and stanchions, and the windows have iron frames also in good electrical connection with the metal walls. The building thus forms a metal shell, and affords complete protection to its contents against any electrical disturbance from outside.

CHAPTER IV

ELECTRIFICATION BY MECHANICAL MEANS

It has been shown in the last chapter that potential may be considered as an attribute of space produced by the presence of a charged conductor. In every point of the space surrounding such a conductor, there acts a force pushing positive electricity one way and negative electricity the opposite way. If the charged body is positively electrified, the potential will be positive all around it, but higher close to the body and lower the farther we recede from it. We must conceive a charge as a something which is adhering to a conducting surface; where there is no conductor there can be no charge, though there may be potential. Now the very definition of a conductor is a body over the surface of which electricity can distribute itself without hindrance, that is to say, only under the influence of the potential force that pushes it. The region of space surrounding the charged body

in which the potential has a sensible value is called the "electric field." A unit charge brought into any point of this field will experience a force acting in a certain direction; in the case of the field being due to the presence of a charged sphere the force acts either radially outward from or radially inward to the centre of the sphere. Where the conductor is of a more complicated shape, or where it is surrounded by a conducting surface kept at a different potential, for instance, earth potential or zero, there also corresponds to each point of the electric field a particular direction, and obviously one direction only, along which the force acts. A unit positive charge, liberated in any point of the field, will follow the impulse of that force and move from point to point along a particular line, and we may thus speak of a "line of force," meaning thereby the path along which a unit charge, or in fact any charge of positive electricity, is urged.

This conception of lines of force, as characterising the qualities of an electric field, is due to Faraday. Thus far lines of force merely have a geometrical significance, namely, that of the direction of the electric force, but it is easy to see that they must also have a

dynamic significance. Obviously if we move along a line of force, the actual magnitude of the mechanical force experienced by the unit charge does not necessarily remain the same. Take the simple case of the field due to a charged sphere hanging free in space. The lines of force are all straight lines converging to the centre of the sphere. If at a distance of one yard our unit charge is repelled with a certain force, then at a distance of half a yard the force would be quadrupled. Thus, although we may travel along one and the same line of force, the magnitude of the force changes inversely as the square of the distance. As we approach the sphere, the potential increases inversely as the first power (not the square) of the distance. Potential and force are two things of different character, namely, energy and mechanical force respectively. We have seen that potential may be considered as an attribute of space, and the idea lies near to also consider electric force as an attribute of space, although as an attribute of a different character. This attribute is a mechanical force, namely, the force exerted on unit positive charge.

Let us see how we could make a mechanical model of the lines of force emanating from a

charged sphere. We might represent each line by a straight wire stuck into the surface of the sphere and pointing true to the centre. We should thus get a kind of spherical hedgehog; to represent a strong field due to a large charge we should stick into the sphere more wires, and to represent a weak charge we should use a smaller number of wires, but in all cases the wires would be evenly distributed all over the sphere. An imaginary sphere, laid round the nucleus from which all the wires spring, will be pierced by all the wires whatever may be the radius of this imaginary sphere, but the number of wires piercing a unit of the surface of the imaginary sphere will be inversely proportional to the square of its radius. But we know that the force is also proportional to the inverse square of the distance from the centre. The two things follow the same law, and it is therefore obvious that by a suitable selection of units we may express the force at any point by a number indicating how many wires pierce a unit of the surface of the imaginary sphere laid through the point. Thus the density of the lines of force passing through the surface at the point in question is a measure of the mechanical force exerted on unit charge at

that point. This is the dynamic significance of the conception of lines of force introduced by Faraday. The density, or number of lines to the unit surface is called the electric "induction," and the force experienced by unit charge is, then, simply equal to the induction, whilst the mechanical force experienced by a body charged with q units will be q times as great. Writing the symbol B for the induction, the force is given by the formula

$$F = B \times q$$

B may be considered as of the nature of a flow of force, or "flux," piercing each square centimetre of the imaginary sphere laid through the point in question, and the total flux emanating from the charged nucleus will then be represented by the product of B and the total surface of the imaginary sphere laid round it. It will also in our mechanical model be represented by the total number of wires we have stuck into this nucleus. But the total number is the same whatever be the radius of the imaginary sphere. To get the relation between original charge Q on the nucleus and total flow of force emanating from it, we may therefore choose any radius,

By adopting a radius equal to unity we get for the surface the expression 4π, and for the total flux the expression $\Phi = 4\pi B$. We know that the force on unit pole at unit distance is $\frac{Q \times 1}{1^2} = Q$. We also know that the force is $B \times 1 = B$, from which it follows that B and Q are numerically equal, and hence we find as an expression for the total flux emanating from Q units of electric charge

$$\Phi = 4\pi Q$$

The conception of lines of force is very useful in forming a mental picture of the properties of an electric field by mechanical analogy, but the analogy must not be taken in too literal a sense. We must not think of lines of force in the same way as we think of the stalks of corn in a field, namely, as physical lines each bound to a definite position. In adopting such a view we would be met at once by the difficulty that our unit charge, being placed midway between two lines of force, would not experience any force. This is contrary to experiment; we cannot find any place in a field of sensible magnitude where the force acting on unit charge is zero. To escape the difficulty some writers use the expression

"tube of force" instead of line of force, thereby indicating that the force is not limited to a particular mathematical line, but acts with equal strength in any point of the same transverse section of the tube.

Let us now apply the conception of lines, or tubes of force, to see what must happen if a non-charged conductor is approached to a charged conductor. In Fig. 2 the circle on

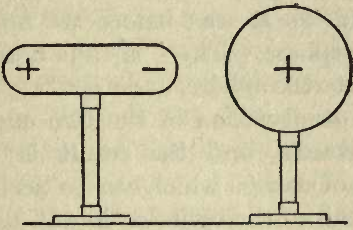

FIG. 2.

the right represents a sphere charged with positive electricity. On the left is a cylinder with rounded ends containing no charge originally. Each tube of force emanating from the charged sphere has the property of pulling negative electricity towards the sphere and pushing positive electricity as far away from it as possible. These forces produce a separation of the two electricities originally combined on the non-charged cylinder, so that

the end pointing to the sphere will become negatively and the other end positively electrified. The question is, how strongly? Obviously it is a matter of conflicting forces. The left end of the cylinder contains positive and the right end negative electricity. If the sphere were taken away, the attraction between the two charges would cause them immediately to flow together, and, neutralising each other, the cylinder would again appear uncharged, as it was before we approached it to the sphere. There is thus a separating force due to the sphere, and a uniting force due to the mutual action of the two ends acting simultaneously, and the result is that the quantity of charge which can be accumulated on each end of the cylinder is not unlimited.

Now let us touch the cylinder with the finger. The negative charge has no desire to flow away through our body to earth, for it is attracted by the charge of the sphere, but the positive charge of the cylinder is pushed away by the action of the tubes of force and will flow as far as it can. Before the cylinder was touched it went to the farthest point, namely, the left-hand end of the cylinder, but the moment we touch it we give it a path to flow much farther, namely, through our body to

earth, that is, right away to zero potential. We have thus brought the potential of the cylinder to zero, and increased the potential difference between sphere and cylinder. We have strengthened the tubes of force passing from sphere to cylinder. The total flux emanating from the sphere has not altered, for that is strictly limited by the charge originally on the sphere, but whilst with a sphere free in space the flux is evenly distributed all round, we have, by bringing the cylinder near, and especially by discharging its positive electricity to earth, disturbed the symmetrical field of the sphere, making it much denser on its left half, and thus increased the inductive effect on the cylinder. The charge at its left end will be increased. If we now interrupt the connection to earth, we have a negatively charged cylinder, and we may carry this charge to some third conductor, and by touching it with the cylinder impart to it a negative charge. This process may be repeated. Approach the cylinder to the sphere again, discharge the cylinder to earth, then pick it up by its insulating stand and carry it again into contact with the third conductor and so on.

By this process the third conductor becomes negatively charged without the use

of a frictional machine or voltaic battery. The third conductor, then, becomes the nucleus of an electric field, and as we know that an electric field cannot be produced without the expenditure of energy, the question arises where that energy comes from. A moment's consideration will show that the energy is given by our hand in carrying the cylinder to and fro. Whilst approaching the uncharged, or weakly negatively charged, cylinder to the sphere we receive energy. There is attraction, because the negative end which is attracted is always nearer than the positive end which is repelled. After the cylinder has been discharged to earth there remains only attraction, and against this attractive force the cylinder has to be pulled away. Here our hand is called upon to impart energy to the system. We electrify the third conductor by the expenditure of energy, that is, by mechanical means. The more often we carry the cylinder to and fro, the more negative electricity do we accumulate on the third conductor, but it is evident that this process cannot go on for ever. We are only able to accumulate a definite charge on the third conductor. As this becomes charged, its tube of force also

develops and finally becomes as strong as those of the sphere. Then the third conductor refuses to take any of the negative charge of the cylinder, and the process of accumulation ceases. If we wish it to go on further we must increase the source from which the negative charge of the cylinder is derived, that is, we must charge the sphere more strongly. How are we to increase this positive charge? The most obvious thing is to increase it also by mechanical means, much in the same way as we increase the charge on the third conductor, and this is the principle on which the modern electric machines, the so-called "influence machines," work.

The process is not carried out in the primitive manner here explained merely by way of elucidating a principle, but still the essential feature is retained of a go-between, or carrier of small charges, between the two conductors on which the electricities of opposite sign are to be accumulated. A familiar example of a practical way of making use of this principle is the electrophorus, but I shall not discuss it here, as it may be found in any elementary textbook. I prefer to deal at once with apparatus in which the principle of accumulating action is carried on

automatically. It is only apparatus of this kind which has practical importance.

As an example of a very simple kind of automatic apparatus we may take Lord Kelvin's "water-dropping machine." Let,

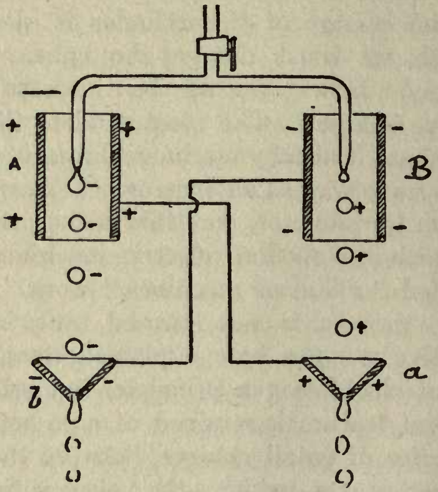

Fig. 3.

in Fig. 3, A and B be two metal cylinders supported on insulating stands, and *a* and *b* two metal funnels likewise supported. A and *a* are connected by a wire; B and *b* are similarly connected. To indicate that the two connecting wires at the crossing point in

the drawing do not touch, one is shown as going round it in a little half-circle. This is the usual method used in electrical diagrams of showing that two wires cross without touching. Owing to the metallic connection established by these wires, the potential of A is always the same as the potential of *a*. Similarly B and *b* are at the same potential. Into the middle of each cylinder there is carried the discharge nozzle of a water pipe, and the flow of water is regulated by means of a stop-cock in such manner that there shall be no continuous stream, but a succession of drops.

The drawing is only diagrammatic, and does not represent the actual shape of the parts. In conductors intended for the accumulation of a charge, all sharp corners must be avoided so as to minimise dispersion of charge, which is strongest the smaller the radius of curvature. Any corner is in reality a curved surface, but with a very small radius of curvature. The different parts of a charge distributed over any surface repel each other. If the surface is quite plane the repelling force between the elementary particles of the charge is parallel to the surface, and there is no component tending to flake electricity off the surface and disperse it into the air. If the

surface is curved there is such a component, and it becomes the greater the more sharply the surface is curved. At a sharp corner it becomes very great, and if the corner is drawn out into a sharp point the force is so great that all the charge is dissipated as soon as brought to the conductor. Hence lightning-rods, which are intended to dissipate any charge which may be induced in a building by a charged cloud overhead as quickly as possible, and so avert the threatened stroke, are provided with sharp points. The gilding is not essential, but more in the nature of an extravagant refinement. The only excuse one can find for such a refinement is that gilding protects the iron from rusting, and so preserves the sharpness of the point. In the water-dropping machine we would, of course, also avoid the sharp corners by making the outside of each part more or less spherical, without, however, altering the inner and essential parts.

The connection between Figs. 2 and 3 will be obvious at a glance. The cylinder A corresponds to the charged sphere, and the drop of water hanging from the end of the pipe corresponds to the right-hand end of the cylinder. It becomes negatively electrified by induction, and on falling carries this

negative charge to the funnel *b*. This produces a small increase in the negative charge on the inducing cylinder B. The drops of water falling through B are positively electrified, and on striking the funnel *a* give up their charge to it, which accession of charge is conveyed to the inducing cylinder A, making it more efficient for charging the drops of water which pass through its interior. We have thus a cumulative action between the inducing cylinders, the drops of water and the collecting funnels. The limit of this cumulative process is reached when the dispersion of charge, due to the growing potential difference, just balances the accession of charge carried by the drops of water from one inducing cylinder to the other. We have here a case of electrification by mechanical means, namely, the motion of drops of water. The energy represented by the electric field between A and B is derived from falling water.

The use of water in an apparatus for producing electrification is not always convenient, and under certain circumstances, as, for instance, on board ship, quite impossible, because in a sea-way the drops would not fall plumb into the collecting funnels. But it is precisely in submarine telegraphy generally,

and also in the process of laying submarine cables, that some apparatus for producing strong electrification is required. This need arises in connection with a receiving instrument known as the syphon recorder. If a permanent record of the telegraphic message is desired, the receiving apparatus itself must write down this message, not in actual letters, but in certain telegraphic code signs on a moving strip of paper. To use a pen in touch with the paper is out of the question, because the mechanical force exerted by the mechanism of the receiving telegraph instrument is, with the feeble electric currents that can be got to pass through a submarine cable, too small to overcome the friction between paper and pen. In order to allow the pen to move unfettered and write freely it must not touch the paper. This is done by using for a pen a capillary glass tube and electrifying the ink. We have then a conductor, namely, the ink, with a fairly sharp point, namely, the capillary end of the tube. It was shown above that the force which causes electricity to flake off from a conductor is very great at a sharp point, and thus the electricity dispersing from the end of the tube takes the ink with it, thus squirting it against the paper. In this manner the slight

and unfettered movements of the pen are recorded on the paper without the pen touching it.

The problem, therefore, is to keep the ink electrified notwithstanding that some of the charge is continuously dissipated in the action of squirting the ink on to the paper. It is necessary to replenish the charge, and the apparatus for this purpose, which is also

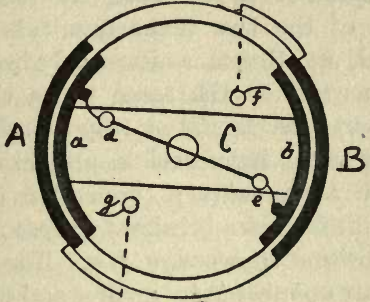

FIG. 4.

the invention of Lord Kelvin, is called the "replenisher." The apparatus gives the original charge and replenishes it from time to time. All the telegraph operator has to do is to twist a knob quickly. Fig. 4 is a diagrammatic representation of the essential parts of Lord Kelvin's replenisher. A and B are two segments of a metallic cylinder, insulated from each other and connected respectively

to the two conductors *g* and *f*, between which a difference of potential is to be established or kept up—in our case ink and paper. Within the cylindrical cavity is another pair of insulated segments *a* and *b*, connected by an insulating bridge-piece C mounted on a spindle, by which the inner system may be revolved. The knob above mentioned is fixed to the end of this spindle. By twirling the knob rapid rotation of the two inner segments can be produced, and thus *a* is alternately brought to face A and B at the same times that *b* is brought to face B and A respectively. The inner segments have each a projecting piece by which a momentary connection is established with fine wire brushes. These are fixed in the position shown *d*, *e*, *f*, *g*. The brushes *d* and *e* are connected by a wire, and the other two brushes are connected as shown with the outer segments.

To explain the action of the replenisher, let us start with the assumption that A has a small positive and B a small negative charge. It is immaterial how small these charges are, since, as will be seen presently, the action is cumulative, so that the merest trace of a charge quickly grows to a quite formidable value. It may be here mentioned that the same principle

is utilised in the well-known electric gas-lighters, where the whole of the mechanism diagrammatically represented in the sketch Fig. 4 is contained in the handle of the instrument. The rotation is produced by pressing a knob, and the cumulative action is vigorous enough to raise the potential of the two outer segments to sparking-point. The spark is produced at the end of a tube, which is held over the issuing gas-jet.

Let us then assume that there is a very feeble charge on A and B. If A is positive, *a* will receive a very small negative charge and *b* a very small positive charge. Let the rotation be clockwise. As the inner segments advance, the contact at the brushes is broken, and the negative charge of *a* is carried towards B. When the inner segment *a* has made a quarter turn, its contact piece touches the brush *f*, and thus the feeble charge is given up to B, making its charge just a little stronger than it was at starting. At the same time the feeble charge on *b*, which is positive, is given up to A, making also that charge a little stronger than it was. After half a turn from the start the segments *a* and *b* have changed places. They are again in contact by the brushes *d* *e*, and *b* acquires now a negative and *a* a positive

charge which they carry forward and give up to B and A respectively, again increasing the original charge. Thus at each half revolution of the internal carrier the charges on the outer segments are increased, the process being cumulative, but also in this case limited by the dispersion of electricity, which, with an increasing potential difference, eventually reaches so high a value that the charge brought in each half revolution by the carrier just balances the leakage of electricity during the time it takes to perform the half revolution. The faster we twirl the knob, the shorter is this time, and the smaller the leakage per half revolution. By twirling faster a higher potential between the outer segments can be attained. This means in the electric gas-lighter a more vigorous and effective spark.

When it is required to accumulate large charges and to produce spark discharges of considerable magnitude, machines on a larger scale must be used. These are known under the name of "influence machines." Such machines have been constructed by Toepler, Holtz, Voss and others, but the type most commonly used in England is that designed by Wimshurst, of which Fig. 5 is a diagrammatic representation. Two discs of highly insulating

material, such as ebonite or varnished glass, are set co-axially very close together, and supported on horizontal spindles which have opposite direction of rotation. Each disc has pasted on the outside a large number of segments of tinfoil. On each side of the

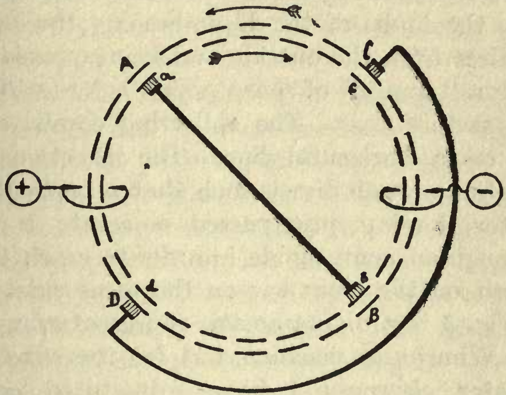

FIG. 5.

pair of discs there is fixed a metal bar diametrically across, and provided at its two ends with fine wire brushes just touching the row of sectors as they sweep by when the disc revolves. These two metal bars are set with an inclination of about 45 degrees to the horizontal, but not in the same direction, so that the angle they include is about

90 degrees. The angular setting of the bars may be altered between about 60 and 90 degrees, so as to get the most efficient condition of working. In addition to the two bars with their four brushes, there are the two devices for collecting the electricities of opposite sign. Each consists of a U-shaped rod, the limbs of the U embracing the pair of discs from the outside and being provided with a " comb " of sharp points before which the sectors pass. The collecting combs are set on a horizontal line. The direction of rotation of each disc is such that a particular sector, having just passed a comb, turns through an acute angle in order to reach the brush on the cross bar on the same side.

Fig. 5 is a diagrammatic representation of the Wimshurst machine, but for the sake of greater clearness I have substituted concentric cylinders for the parallel discs. The direction of rotation is shown by the arrows. Let the inner cylinder represent the front disc, and the outer the disc at the back. The discs themselves are not shown, only the segments which are represented by the short lines. The cross bar for the front disc is shown by a straight line, that for the back disc by a curved line. This is done merely to

avoid lines crossing each other and thus rendering the diagram less clear. Electrically, a curved conductor is as good as a straight one. The collecting devices are represented by the two pairs of points facing the segments on a horizontal diameter. The conductors in which the charges are accumulated are shown by the circles into which a plus and minus sign is inscribed.

To explain the action of the machine, let us assume that by some means a very slight difference of potential has been imparted to two opposite segments of the outer cylinder, say to the segments A and B. This may be done by approaching a rubbed stick of sealing-wax, but generally such a difference of potential exists naturally. We cannot walk across a dry carpet, or run the hand along a piece of furniture, without producing some slight electrification which has the effect of setting up potential differences between different points of space, and, as the merest trace of such a potential difference suffices to start the cumulative process, machines of the Wimshurst type generally start without the necessity of previous electrical excitation. It suffices to turn the handle and so cause the discs to rotate in the proper sense. Let us

then assume that the potential of the segment A is a little higher than that of segment B; in other words, that A has a very slight positive and B an equally slight negative charge. The cross bar with the segments *a b* is at that moment very much in the same condition as the cylinder in Fig. 2, that is to say, the end pointing to the positive segment A (which takes the place of the sphere in Fig. 2) becomes by induction the place where a negative charge collects, and the end *b* the place where a positive charge collects, only the induction is augmented because B also influences the induced system in the same sense. As the inner cylinder revolves, *a* moves to the right and is detached from the brush on the cross bar, and takes its charge with it. The same happens with the segment *b*, which takes its positive charge to the left. The segments *a* and *b* eventually arrive in the positions *c* and *d* respectively. In this position they come opposite to two outer segments C and D. The rôles are now reversed; it is the charge on the inner segment which produces a displacement of electricity along the cross bars connecting C and D, and the charges on these segments are carried on as the outer cylinder rotates, C moving

to the left into the position previously occupied by A, and D moves to the right into the position previously occupied by B. But the charge on C is of the same sign as that with which A started the process, and will therefore act in the same sense, only more strongly, since it has been reinforced by the inductive action just explained. Thus during rotation of the two rows of segments in opposite sense the original very slight electrification is rapidly increased, and a considerable quantity of electricity may be taken off by the action of the collecting combs and accumulated on the electrodes. It will be observed that the segments of both discs, whilst passing each other on the horizontal diameter, are charged with electricity of the same sign, namely, positive on the left and negative on the right.

If we now inquire as to the true cause of electrification, we find that apart from the quite insignificant initial charge on A and B, it is simply the mechanical energy required to produce rotation against the opposing force of electrostatic attraction between the outer and inner segments. A has a positive, and *a* has a negative charge. These two segments therefore attract each other; as *a* moves to the right and A to the left, they are

pulled apart against this attractive force, and energy is therefore required to produce this motion. It is this energy which, by the action of the machine, is converted into the potential energy represented by the electric field surrounding the two electrodes. To increase the charge it is customary to connect the electrodes with the knobs of two Leyden jars, since by the use of a condenser the quantity of electricity, which can be accumulated with a given difference of potential, is greatly augmented. That energy is used in producing electrification is distinctly felt when working the machine by hand. The machine gets charged after a few turns of the handle, and the operator feels that, as the charging progresses, it gets harder to turn the handle. In large machines the manual work becomes so heavy that it is convenient to use an electric motor for working the machine.

CHAPTER V

THE ELECTRIC CURRENT

IN Chapter II use has already been made of the term electric current. The term meant the transfer of a positive charge through a wire from a point where the potential is higher to one where the potential is lower. Observation shows that the quantity which can be transferred in unit time depends not only on the difference of potential, but also on the material and the cross section of the wire. A stout wire will transfer a bigger quantity in unit time than a thin wire, or, as we may also say, it is able to carry a bigger current. When it is a question of electricity in motion the conductor must have body, whilst as we have seen, with electricity at rest only the surface counts, or, to speak more correctly, only the capacity counts. But the capacity of a sphere in space, or of a Leyden jar, is quite independent of the thickness of the metal parts. A wooden sphere covered with the thinnest layer of gold-beater's skin will at the

same potential hold exactly the same quantity of electricity as if it were made of solid brass or lead or any other metal. Electricity at rest resides entirely on the outside of a metal conductor. We might reduce the thickness of a shell to any degree, and still the charge is not altered.

Now let us follow this fact to its logical conclusion. What will happen if we reduce the thickness of the shell to zero? If thickness has nothing to do with the capacity, then by reducing it to nothing at all we should not alter the capacity. In other words, the body which holds a charge need not be a conductor at all. Its conducting property is only necessary to let the charge distribute itself over the whole of its surface, in fact to get a charge on to it at all. If, however, the charge is not transferred to the surface from outside, but actually produced on the surface, then there is no need that the surface should be the surface of a conductor. This will be clearly seen if we reflect that a glass rod, although a very good insulator, may be electrified by rubbing. Its insulating property is a positive advantage, since we may hold one end in our hand and yet electrify the surface at the other end. The charge is not able to slip about freely over the whole

surface, as is the case with a charged conductor; hence, if we touch a particular point of the electrified part, we take off a little of the charge at that point, but the rest of the rod remains charged. We thus see that a charge can reside on the surface of an insulator, and it can be proved experimentally that the charge even penetrates a little way into the body of the insulator.

If a Leyden jar or a paper condenser be discharged and left standing a little while, a second though very much weaker discharge may be taken from it. It is as though the electricity had soaked into the body of the dielectric and some of it was thus prevented from getting out at the first discharge. When the jar has apparently been completely discharged, there is still left a small residual charge, which slowly leaks out on to the surface of the glass and is then ready to produce a second discharge spark. If the dielectric is mica, this phenomenon of soaking is much less pronounced, and if air is used as a dielectric, it is absent.

A very striking experiment may be made to show that the charge in a Leyden jar does not reside on the surface of the metal coatings, but on the surface of the glass. Imagine a metal

beaker into which fits a glass beaker and into that a second metal beaker. The latter may have a stem and discharge knob much in the same way as an ordinary Leyden jar, the only difference being that the inner and outer coatings are not pasted on to the glass, but are removable. If, after charging this jar, we take out the inner metal beaker by insulated tongs, and also remove the glass beaker from its outer envelope, we have completely dissected the jar. The two metal coatings may be handled, the glass may be picked up by the hand touching the outside, and yet when we put the Leyden jar together again, we find that it still contains the original charge, less a certain unavoidable leakage, since no insulator is perfect. We thus see that any body, whether insulator or conductor, may hold a static charge on its surface.

Why then do we make the electrodes of an electric machine, such as that diagrammatically represented by Fig. 5, of brass and not of glass? For the simple reason that a glass electrode, although quite capable of holding a charge, is very ill-adapted for receiving it. The charge must be conveyed to it by a wire, and from the point where the wire joins it the charge must be able to flow to all points of the surface.

This flow is impossible through the body of the glass, since glass is an insulator. Conversely, if we touch a charged glass sphere at one point we may take off a little of the charge, but not the whole of it, which is distributed over the sphere. Between electricity at rest and in motion, or as we may also say, between static charges and currents, there is thus the fundamental distinction that the static charge requires surface and the moving charge body.

The greater the current we wish to convey, the stouter must be the wire. The commercial unit of current is the Ampere, so named after the great French physicist. We may define the current existing in a particular point of the wire as the number of unit charges which pass that point during one second. The magnitude of the electrostatic unit of quantity has been defined in Chapter I, p. 13. By experiment it has been proved that one ampere is represented by the passage of 3000 millions of such units per second.

Man has no sense by which he can estimate the strength of a current flowing in a wire—by touching the wire he may get a shock and thus conclude that the wire is at a higher potential than he is himself when standing on the earth; and indeed wiremen, who have

grown reckless in their calling, often resort to this simple test to find out whether a wire is what is technically termed "alive," but no amount of shocks will ever enable a man to say how many amperes are flowing in the wire. This can only be determined by observation of certain effects produced by the current. These effects may be chemical, thermal, magnetic or mechanical.

Chemical action of an electric current.—The substance of a copper wire carrying a current undergoes no change. It may get heated whilst the current flows, but chemically it remains unaltered. Even if the wire is an alloy of two metals there is no change in its chemical nature. Also with liquid conductors, such as mercury or molten iron, the passage of a current does not produce a chemical change, but if the liquid is some chemical compound there is such a change. Imagine two copper plates placed in a solution of copper sulphate and provided with terminals AB, such as shown in Fig. 1, p. 48. Attach to these terminals the wires leading to a dynamo machine or some other source from which an electric current flowing always in the same direction may be obtained. Let us also put into the circuit some instrument

which will record the total quantity of electricity that has passed through the solution in a given time, such as a recording electricity meter used in the sale of electricity to householders. We shall find that the copper plate at which the current enters gets gradually thinner, and that at which the current issues gradually stouter exactly in the same measure, showing that the current has the effect of transporting copper from the one plate to the other.

An arrangement of this kind is called an electrolytic cell, and the process going on in the cell is called electrolysis. The plates are called the electrodes, and the liquid between them is the electrolyte. The electrode by which the current enters is also called the anode, and that by which it leaves is called the kathode. The current flows from the anode into the electrolyte and from the electrolyte to the kathode, taking the copper with it. If instead of copper sulphate the electrolyte contained some other metallic salt, the current would split this up chemically and take the metal, whatever it may be, with it and deposit it on the kathode. This is the principle on which objects are silver- or nickel-plated. It is also the principle on which copper is refined on a large scale. The

anode is a block of impure copper, and is gradually dissolved by the passage of the current. The dissolved copper goes into the solution, and out of this only the pure copper is transported by the current and deposited

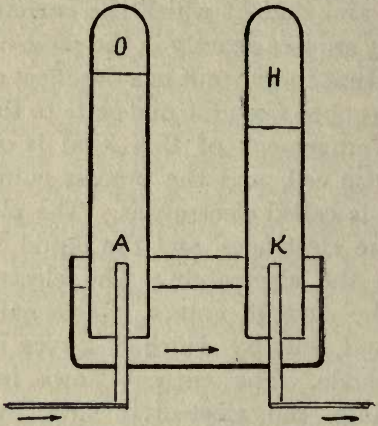

Fig. 6.

on the kathode, the impurities falling to the bottom of the cell as a sludge.

The reader may ask, what happens if we use as metal for the electrodes platinum which resists chemical action? In this case the electrodes act simply as collectors for the substances which are being extracted out of the electrolyte by the current. Let us take

the simplest case of the electrolyte being water, which has been rendered conducting by a slight addition of some chemical, such as sulphuric acid. The two substances out of which water is formed are the gases oxygen and hydrogen. The current, in passing through the water, tears these oxygen and hydrogen atoms asunder and carries them off, the hydrogen in the direction of its own flow, namely, to the kathode, and the oxygen in the opposite direction, that is to say, to the anode. Here the gases are deposited in the form of bubbles, which from time to time become detached and rise to the surface. By using an arrangement such as shown in Fig. 6 the gases may be separately collected and their volume measured. A and K are two platinum wires fused into the bottom of the glass vessel, which is filled with acidulated water. Over these electrodes are placed two inverted glass tubes also filled with water and closed at the top, so that the gases liberated at the electrodes may be collected and their volume measured. It is found that the space filled by hydrogen, H, is exactly twice as great as that filled by oxygen, O; and this is precisely the volumetric proportion in which these two gases form water. The direction

of the current is shown by the arrow. There is a migration of hydrogen atoms in the direction of the arrow through the liquid, and a migration of oxygen atoms in the opposite direction. We actually see the bubbles forming on the kathode and anode, yet we see no bubbles passing through the liquid. The formation of bubbles shows that there is actually a tearing apart of the two gases close to the surface of the electrodes, but apparently there is no such tearing apart in the body of the liquid, for we see no bubbles there.

This apparent anomaly has been cleared up on the basis of an hypothesis by Grotthus, which may be put in homely language by reference to a ball-room. Let each male dancer stand for an oxygen atom and each woman for a hydrogen atom. Let the room be crowded, and all the dancers be properly paired. A man looking down on the throng sees only couples, but no single persons. Now suppose that by some rule of the dance, at a given signal one man at one end of the room must leave his partner and cling to the wall, whilst at the same moment a woman at the other end of the room must do the same. This will disturb the homogeneity of the throng, but that can immediately be

restored if all the couples in a direct line between the two walls change partners and thus absorb the two partnerless persons again into the general dancing throng. Our observer on the gallery would then not notice any difference in the assembly; all remain properly paired.

The electrolysis of water is commercially utilised for the production of pure oxygen and hydrogen. The electrodes are of iron, and the electrolyte is a 16% soda solution. The cost of the process, including cost of power, labour, interest and depreciation, varies from 9*d.* to 1*s.* 2*d.* per one cubic meter oxygen + two cubic meters hydrogen, according to the magnitude of the plant and local conditions.

Electrolysis is not confined to liquids; it can also be produced in a solid, provided it is a conductor. Thus, if a current is sent through a lump of caustic potash, it is decomposed into oxygen and the metal potassium. Let, in Fig. 7, P be a platinum plate, C a lump of caustic potash, and M a globule of mercury placed into a cavity hollowed out of the solid electrolyte; then, on the passage of a current in the direction shown by the arrows, oxygen will collect on the surface of the platinum, and

potassium will collect on the under surface of the mercury, forming with it an amalgam. By distilling off the mercury under exclusion of the air, the metal potassium may be obtained in a free state. In this way Davey first succeeded in producing free potassium and sodium; in fact he discovered these metals by electrolysis.

In all these experiments it is found that

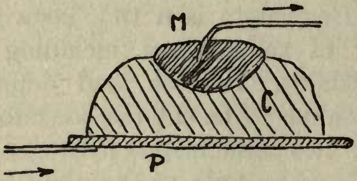

FIG. 7.

the weight of the substances liberated by electrolysis is exactly proportional to the quantity of electricity that has passed through the cell. It is also found that if the same current passes through different cells containing different electrolytes, the weight of the different substances liberated are in the same proportion as their chemical equivalents. These two laws, both discovered by Faraday, are known as Faraday's first and second law of electrolysis. The electrochemical equivalent

of a substance is the weight in grams liberated by the passage of one unit of electricity. The unit here chosen is, however, not the small electrostatic unit as defined on p. 13, but the arbitrary unit called the Coulomb, after the French physicist, and is represented by that quantity of electricity which would accumulate on a conductor if it were charged with a current of one ampere for one second. We may even take a larger unit, such as the ampere-hour, as the unit to which the quantity of electrolytically deposited substances may be referred. The ampere-hour is equal to 3,600 coulombs. The following table gives, for a few substances, the weight deposited by one ampere-hour of electricity—

	Grams per ampere-hour.
Hydrogen	0·037
Oxygen	0·298
Water	0·335
Copper	1·182
Zinc	1·215
Silver	4·032

By means of such figures it is possible to determine beforehand the quantity of electricity which must be passed through a cell in order to deposit a certain weight of metal

on the objects to be treated. Conversely, it is also possible to draw up a balance sheet showing how much zinc will be used up in a voltaic cell relatively to the amount of electricity obtained from the cell. Such a balance sheet shows that the production of electric currents in large quantities by voltaic cells is far too expensive for commercial use. It is only when feeble currents are required that it pays to produce current by electrolytic process; when current is required on a large scale, such as for lighting and power, and also for metallurgical work, copper refining and electroplating on a large scale, it must be produced by dynamo machines. Electrolysis, then, is not of much importance for the production of electricity, but it is of enormous importance in the utilisation of electricity, forming the basis of copper refining and electro-plating, on which large industries carried on in Swansea, Birmingham, Sheffield and other places are built up.

Thermal action of an electric current.—An electric current flowing through any conductor heats it. The amount of heat developed depends on the material of the conductor, its length, cross section and the strength of the current. As the current is increased

the heat increases also, but at a faster rate, so that if the conductor is a wire a point is reached when it becomes red-, or white-hot, and gives out light. This is, indeed, the principle on which incandescent lamps become sources of light. The wire may be a carbon filament, or a filament of tantalum, tungsten, or other highly refractory metal. Whatever the substance used for the filament of a lamp, it is subject to the same influence as any other conductor—it gets hot when traversed by a current. There is, however, this difference in degree. In the lamp we desire to produce heat at a high temperature, for only then do we get light as well as heat; in a conductor used for the purpose of transferring electricity from the source where it is generated to the apparatus where it is utilised, we desire to generate as little heat as possible. There is an advantage in producing a high temperature in the filament of the incandescent lamp, but there is no advantage whatever in producing heat in the wires that carry the current to the lamp. On the contrary, there is an objection to it; not only does the generation of heat mean a dissipation of energy, that is, of something which costs money, but it may be a positive danger, since

a conductor becoming red-hot may set fire to a building.

To guard against this danger a short piece of the conductor is made very thin, so that in the event of the current becoming so strong that the rest of the conductor becomes sensibly hot, this little piece shall become so hot that it fuses, and thus interrupts the continuity of the conductor, that is, causes an interruption of the current. This is the principle of protecting electric circuits against overheating. The short bit of the conductor, intended by its destruction to save the rest, is called the fuse, and this is so placed that by its melting it cannot cause a fire. Such fuses are found in every domestic installation for lighting. The fuse wire is enclosed in a tube or plug of porcelain, and sometimes the cavity is filled in with carborundum powder to act as an absorbent of the heat momentarily generated by the explosive fusion of the wire.

In this connection it is interesting to note that the seemingly obvious is not always the best. At first fuse wires were made of tin or lead, simply because these metals fuse at a low temperature, and it seemed obvious that the lower the temperature of fusion the quicker would the device act. This is a fallacy. If lead or

tin are used for the fuse wire, this must be much stouter than would be the case with copper or silver; consequently the amount of material, which by the heating is volatilised, becomes so great that the process resembles rather an explosion than a quiet melting, and the envelope may be shattered, letting out the flash, and thus the fuse itself may become a source of danger. In this respect the best material for fuse wires is silver. An exceedingly thin silver wire will carry a fairly large current, and if the current should rise to a dangerous value and the wire be fused, the amount of material volatilised is so small that there is hardly any explosive effect, especially if the wire is embedded in carborundum powder.

Now the reader may ask, why should a thin silver wire suffice if for the same current a stout lead wire is necessary? This comes from the physical fact that silver is far better adapted than lead for carrying an electric current, it conducts better, or, as we also may say, it has a higher "conductivity." By this we mean that to get the current through the wire the force which is pushing the electricity from one end to the other is much smaller with silver than with lead; silver offers less "resistance" to the flow of electricity than lead.

Thus each conductor has a certain physical property called its electric resistance, and this depends on the length and section of the conductor, on its temperature and on its material. In order to compare different materials as regards resistance, we must eliminate those elements which may vary from case to case and reduce all to the same standard. The physicist takes as the standard length the centimetre, and as the standard cross section the square centimetre. The standard form for which the resistance is given is thus not a wire at all, but a cube. The engineer prefers to retain the shape of the wire for his standard, and defines the resistance of the material as that of a wire one metre long and one square millimetre in cross section, the test being made at the temperature of 15° C.

How is such a test to be made ? G. S. Ohm, a Bavarian physicist (1787–1854), was the first to make such tests and to formulate a law, which bears his name, and which connects the three things on which the transfer of electricity from one end of a conductor to the other depends. Ohm found experimentally that the strength of the current is directly proportional to the e.m.f. applied at the ends of the wire, and inversely

proportional to a particular physical property which he called the "resistance" of the wire. Expressed mathematically, Ohm's law is

$$I = \frac{E}{R}$$

where I stands for current strength, E for electromotive force, and R for resistance. He also found that in a double length of wire the same e.m.f. will only produce half the current strength, whilst by increasing the cross section of the wire (which can conveniently be done by using two or more wires side by side), the current strength is proportionately increased. He thus found that the resistance of the conductor is directly proportional to its length and inversely proportional to its section. This, again expressed mathematically, is

$$R = \varrho \frac{L}{q}$$

where L is the length and q the section. The coefficient ϱ depends on the material, and is called "the specific resistance." The two formulæ here given are generally valid, whatever may be the system of units chosen. They may, therefore, also be used with the practical units of the "ampere" for current

strength and the "volt" for e.m.f., in which case the unit of resistance is called the "ohm." The following table gives the specific resistance reduced to a standard wire one metre in length and one square millimetre in cross section at ordinary room temperature—

Material.	Resistance in ohms.
Silver	0·0158
Copper	0·0165
Aluminium	0·0287
Iron	0·125
Mercury	0·953
Platinum	0·094

The fact that a column of mercury one metre long and one square millimetre in section has a resistance of nearly an ohm, has led to suggestions to adopt mercury as a standard of resistance, and indeed, before the true value of the ohm had been determined by electrodynamic investigation, the mercury column was taken as approximately representing an ohm. It might be thought that such a standard would be acceptable to physicists, because it would enable each investigator to reproduce the standard at any time for himself, and thus render him independent of others. It is, however, not at all easy to produce such a standard. There is not only the

difficulty of obtaining a glass tube of absolutely even bore, but the further difficulty that the specific resistance of mercury, as of all metals, varies slightly with the degree of chemical purity in which the metal can be obtained, so that the so-called "mercury standard" has been discarded in favour of standards made of platinum.

Such standards are deposited in State Laboratories or Museums, and only serve as reference standards, such as the yard or the pound. For practical use other so-called secondary standards are made of some less expensive material, generally some alloy, such as German silver, manganin, platinoid, eureka metal, etc. These alloys have the advantage that their resistance is very little influenced by change in temperature, whereas copper increases its resistance sensibly when heated. For every degree centigrade of temperature rise above 15° C., the resistance of a copper conductor rises by about 0·38 per cent. All machines when at work become heated to a certain extent, since some of the energy which is passing through the machine is necessarily lost in the process of conversion from one form to another form. This lost energy is converted into heat, and thus the temperature of

the machine is increased. The more efficient the machine, that is to say, the less of the energy passing through it is lost, the cooler will the machine run. Excessive heating in a machine is also objectionable on the ground that thereby some of the materials used in the construction may be destroyed.

If we have to deal with a dynamo machine this is especially important, since in the construction of such machine insulating materials such as cotton, tape, wood, etc., must be used. The machine should therefore be designed with due regard to a strictly limited temperature rise, and it is also important that the finished machine should be tested so as to make sure that the designer's intention has actually been realised. The heat is generated in the body of the materials used, and it has to leak out and be dissipated into the surrounding atmosphere from the surface of the machine. Thus it is quite possible that the temperature at the surface, which can be measured by a thermometer, is much below the internal temperature, just as the outer surface of a stove is not nearly so hot as the fire inside. To get the temperature of the hottest part, we should put a thermometer to the inside of the machine, but

unless provision has been made in the construction of the machine for such application of thermometers, this may not be done. It is in this connection that the influence of temperature on the resistance of copper comes in very useful. We need only measure the resistance of the copper coils before the machine is set to work, that is to say, whilst it is at ordinary room temperature, and repeat the measurement after the machine has got hot through working. The increase of resistance thus found may be used to calculate the rise of temperature in the interior of the machine. According to the best modern practice, this rise should not exceed about 50° C.

Another important application of the fact that all metals increase their resistance with a rising temperature is made in the so-called "electric pyrometer," an instrument for measuring the very high temperatures in metallurgical furnaces. Essentially, the pyrometer consists of a porcelain tube containing a spiral of platinum wire, which is put into the furnace. The spiral is joined to other wires of low resistance, which lead to some kind of measuring instrument, indicating the resistance of the platinum spiral. The hotter

the furnace, the higher becomes the resistance of the spiral, so that by a suitable graduation of the scale of the instrument, this may be used to show what temperature actually exists in the furnace.

The influence of temperature on the resistance of a material is a physical attribute of the material, such as its specific resistance itself, or, for the matter of that, as all its physical and chemical properties. We express this particular property by saying that the material has such and such a "temperature coefficient." Thus copper has a temperature coefficient of + 0·0038, meaning that the resistance increases by 0·38 per cent. for every degree of temperature increase. The + sign means that the coefficient is positive, that is, refers to an increase, not a decrease of resistance. There are, however, certain substances which have a negative temperature coefficient. In these materials the resistance diminishes as they get hotter. Most liquid conductors have this property, and of solid conductors carbon is a familiar example. The resistance of a carbon filament incandescent lamp is greater when the lamp is cold than when it is alight. In this case the heat is generated by the current passing through

the filament. If then, by raising the e.m.f. of the supply more current passes through the lamp, the filament gets hotter, its resistance decreases, and still more current is permitted to pass. The result of this interaction is that an increase of voltage does not produce a proportional, but an exaggerated increase of current and vice versa, with a corresponding exaggerated variation in the light given. Such lamps are sensitive to changes in voltage, more so than the metal filament lamps which, by reason of their positive temperature coefficient, burn with greater stability.

The most sensitive of all filaments is, however, the pencil of a "Nernst" lamp. This, when cold, is not a conductor at all; to make it conducting it must be heated to a dull red heat by a platinum spiral placed near it in the lamp. When sufficiently hot the pencil becomes a conductor of considerable resistance, so that a much shorter length than the filament of a metal or carbon lamp offers sufficient resistance for a working e.m.f. of 200 or 220 volts. By the passage of the current the pencil is maintained at white heat, and a very brilliant light is emitted. The pencil is, however, very sensitive to changes in voltage. It

has a very large negative temperature coefficient, and in consequence the exaggeration as regards changes in current strength mentioned on the previous page in connection with carbon lamps, is much greater; in fact, it is so great that the working becomes unstable if the pencil be used alone, even on a circuit of perfectly constant voltage. To make the use of such a pencil possible, it is necessary to protect it against excess of current and consequent disintegration. This is done by correcting its negative temperature coefficient by the addition of a conductor having a large positive temperature coefficient. Such a conductor is iron when near the point of red heat. The pencil and this additional resistance, termed technically a "ballast resistance" are arranged tandem-fashion, or, as it is called, "in series," so that the current first passes through the ballast resistance and then through the pencil. The object of the ballast resistance is to keep the current as near constant as possible; and this object is attained by the fact that, owing to the peculiar property of hot iron to very largely increase its resistance for even a slight increase of temperature, the e.m.f. absorbed by the ballast resistance becomes large even with a small

increase of current, so that a further growth of current is efficiently checked. It is in this way that the working of the Nernst lamp is made stable.

The ballast resistance is made of fine iron wire; and if this were allowed to become nearly red-hot whilst exposed to the air, it would very soon burn out. It is therefore necessary to protect this delicate spiral of wire from the air, and this is done by enclosing it in a sealed glass tube. This tube is filled with hydrogen, since hydrogen has, of all gases which could be used in this case, the greatest heat capacity. It would obviously be a mistake to use an exhausted tube as a protecting envelope for the iron spiral, since through a vacuum very little heat can be transmitted, and it is obviously important to prevent the spiral from getting more than dull red-hot, otherwise it would be destroyed. If, then, a gaseous filling is indispensable for the conveyance of the heat generated in the spiral to the outside envelope, we must use a gas which will not burn the iron. Air is therefore inadmissible. Nitrogen or carbonic acid might be used, but these gases do not convey heat so readily as hydrogen, the lightest of all gases, and whose molecules are the most

mobile. Similar resistances are also used as regulating devices in train lighting. Regulating resistances of this kind, but on a much larger scale, are now made for various industrial purposes where it is important to keep a current fairly constant, notwithstanding variations in resistance or e.m.f.

CHAPTER VI

THE DYNAMICS OF ELECTRIC CURRENTS

We have seen that two carriers of static charges, if brought near each other, act upon each other with a certain mechanical force. The same is the case with conductors carrying moving charges, that is to say, electric currents under certain conditions. The two conductors must lie near each other and run more or less parallel. If the two currents flow in the same direction the wires attract each other, if they flow in opposite directions the wires repel each other. The fact that parallel currents flowing in the same direction attract each other may be proved by a very simple experiment: Take a loosely coiled hank of fine, and therefore very flexible, cotton-covered copper wire, hang it over a bar, and send a current through it. Immediately on closing the switch, which completes the circuit through the hank of wire and allows the current to flow, we shall observe a tightening up of the

loose hank into a more compact mass of coils. On opening the switch, the elasticity of the single turns causes them to spread out again from each other. In such a coil all wires carry the same current, they are more or less parallel, and the direction of flow is the same. The force which this simple experiment reveals is but feeble, but in kind it is the same force which comes into play when we use electricity for driving a 1000 horse-power rolling-mill, or a tram-car or a railway train. The difference is merely one of degree as regards the magnitude of the force, and of suitable arrangement of the parts of the machine, so that instead of one spasmodic jerk of the outermost loose coils of our hank we shall get a sustained rotary movement of all the coils.

The increase in the magnitude of the force is brought about by the use of iron. That the increase is very considerable may be shown by a simple experiment: Take two paper tubes about an inch in diameter and four inches long. Wind on each about ten layers of fine cotton-covered copper wire, so as to get a long coil containing about 500 or 1000 turns in all. Leave the two ends of the wire long enough to serve as suspending wires of the

coil. A coil of this kind is called a "solenoid." If two such solenoids are suspended horizontally from their own wires one behind the other, so that the axes are in the same line, with their ends half-an-inch apart, it will be found that on sending a current through them they will either repel or attract each other. If the direction of the current round the spiral of both coils is the same, there will be attraction; if the current direction in one solenoid is reversed, there will be repulsion. In both cases the force is feeble.

Now place into the paper tube of each solenoid an iron core. The force will now be very much increased. If the coils, instead of being suspended, be held fast, and the cores can slide easily within their paper tubes, it will be found that the cores themselves either come together or fly apart according to the relative direction of the current. Thus the presence of the iron not only increases the dynamic force of the current, but it also shifts the seat of this force from the wire to the iron. We are thus driven to the conclusion that the seat of the force, or at least part of it, is not in the wire itself, but in the space surrounding the wire.

The fact that an electric current produces mechanical forces acting through space

was first discovered by the Danish Physicist Oersted (1777–1851), not by the experiment here described, but in a still more simple way. He found that if a wire carrying a current is placed above and parallel to the needle of a compass, the needle is deflected. The deflection is in one sense with the current flowing one way, and in the opposite sense if the current is reversed. The deflection is increased if the strength of the current is augmented, or the wire brought nearer. There is no deflection if the wire is placed not over, but parallel to and at the side of the needle; and if the wire is shifted from a position parallel to and above the needle to a similar position and distance below the needle, the deflection is reversed. Also, if the wire is not exactly parallel to the direction in which the needle points, there is some deflecting force, though this gets weaker as the angle between wire and needle increases. All these facts the reader may, by the aid of a pocket compass, a voltaic cell and a few feet of wire, find out for himself.

To us in 1912 there is nothing remarkable about such an experiment; but when Oersted first performed it in 1820 it was a revelation of enormous import. The scientific world of

those days knew something of electricity, and it knew something of magnetism, but it knew these two things as distinct from each other. Now by one stroke of experimental genius Oersted showed the scientific world that, after all, electricity and magnetism are not independent domains of physics, but are intimately connected. Every physicist in Europe repeated the experiment, and many speculated on the question what really constituted the connecting link between magnetic and electric phenomena. It was Ampere who first formulated a rule by which the direction of deflection could be predicted, and two other French scientists, Messrs. Biot and Savart, gave a mathematical formula by which the magnitude of the deflecting force could be calculated. Ampere's rule is as follows: Imagine yourself swimming in the direction of the electric current and looking at the compass needle. Its north end will then be deflected to your left. Biot-Savart's law may be stated by reference to the force exerted by the current on unit magnetic matter at any given point of the space in the neighbourhood of the conductor.

Before discussing this subject it is necessary to define what we mean by the term "unit

of magnetic matter." It has already been mentioned that it is physically impossible to isolate north from south magnetism as completely as we can isolate positive from negative electric charges. Magnetism always appears as an attribute of a magnetic material, such as steel; and when one end of a steel bar shows north magnetisation, the other shows south magnetisation. Thus a perfect isolation of magnetic matter of one kind is not possible. The isolation can only be partial, but this need not deter us from assuming, merely for the purpose of a definition, that at a particular point, say the end of a long wire, a definite amount of north magnetic matter is accumulated, whilst the corresponding south end of the wire is so far removed that it does not interfere with any test we may make. Imagine, then, that we have in two points of space, D cm. apart, the magnetic masses M and m concentrated. The force acting between them is, by the general law discussed in Chapter I, given by the expression

$$F = \frac{Mm}{D^2}$$

Let M be fixed in space and move m round it on the surface of a sphere, then the same

force will be experienced at any point of the sphere, and the only thing that changes will be the direction of the line along which the force acts. We may in fact, analogous with the argument used in the consideration of the electrical problem, consider the magnetic force as an attribute of space and express it by the product B $\times$ m, where B indicates the density of the magnetic field on the surface of the sphere of radius D. B is the " induction " expressed as so many lines of force per square centimetre of surface, and the product of the total surface of the sphere, with this induction, will give the total flux of force Φ emanating from the magnetic mass M. Since the surface of a sphere is $4\pi D^2$ and $B = \frac{M}{D^2}$, we find the following relation between the quantity of magnetic matter M and the total flux Φ emanating from it—

$$\Phi = 4\pi M$$

We are now in a position to define unit of induction and unit of magnetic matter. If two magnetic masses placed one centimetre apart attract or repel each other with the force of one dyne, then each magnetic mass has unit value. If at any point of space unit

magnetic mass is acted upon with the force of one dyne, then the induction at that point is unity, or, as we also may express it, each square centimetre of a surface laid at right angles to the direction of the force at that point is traversed by one line of force. Thus we may define the horizontal component of the earth's magnetism by saying that the induction is 0·18, meaning thereby that each unit of magnetism accumulated on the north end of a compass needle is drawn northwards with a force of 0·18 dynes, the other end of the needle being drawn southward with an equal force. These forces make the needle point north-south. In a dynamo machine there is also magnetic induction, but of vastly greater intensity. In such machines e.m.f. is produced by the motion of wires placed on an armature, which revolves within a system of magnet poles. The clearance space between the face of the poles and the surface of the armature is traversed by magnetic lines of force, and the stronger the induction in this so-called "air space," the higher is the e.m.f. of the machine. The object of the designer is therefore to produce as strong an induction as possible. In modern machines the induction in the air space is of the order of 5000 to

10,000, and each square centimetre of polar surface contains something like 400 to 800 units of magnetic matter.

We now return to the consideration of Biot-Savart's law. The definition given by them is as follows: The force exerted on unit magnetic mass at a given point (or, as we may also say, the induction at that point), due to an element of the conductor, is given by the expression: product of the length of the element as seen from that point, the strength of the current; and this divided by the square of the distance. Stated in this form the law sounds rather complicated, but it becomes simple enough if we apply it to some special cases. Take, for instance, a circular conductor. The induction in its centre, produced by an element of one centimetre length of the conductor, would be simply the product of the current multiplied with the visible length (in this case also a centimetre), and this divided by the square of the radius R. Since in the whole circle there are $2\pi R$ such elements, the induction, due to the whole of the conductor carrying a current J, is

$$2\pi R \frac{J}{R^2} = \frac{2\pi J}{R}$$

The force acts at right angles to the plane of the circular loop. A unit pole will therefore be drawn through the loop with the force

$$B = \frac{2\pi J}{R}$$

By means of this formula we may now define unit current. If $J = 1$ and $R = 1$, then $B = 2\pi$. Now imagine a wire bent into a circle of 1 cm. radius. If unit pole in the centre of this circle is drawn through it with a force of 6·28 dynes, then there is unit current in the wire. This so-called electromagnetic unit of current strength is too large for practical work, and for this reason a unit ten times smaller is adopted. This is called the ampere.

The coil exerts a force $F = \frac{2\pi Jm}{R}$ dynes on the magnetic mass m placed in the centre of its plane, but since action and reaction must always be equal, this is also the force with which the mass m acts on the wire. The induction due to m in the space occupied by the wire is $B = \frac{M}{R^2}$, and by combining the equations for F and B we find $F = 2\pi RJB$ dynes.

This is the force experienced by a wire of

2πR cm. length, carrying a current of J units in a field of induction B. Generally, writing l for the length of the wire in cm., and expressing current strength in amperes, we have the force in dynes

$$F = \frac{J}{10} lB$$

Let us apply this to the wire on the armature of a dynamo machine. Suppose the armature is 10″, or 25·4 cm. long, and the induction is 8000. With a current of 50 amperes through the wire we have a tangential force of

$$F = \frac{50}{10} 25{\cdot}4, \ 8000 \text{ dynes};$$

or,

$$F = 1{\cdot}03 \text{ Kg., or } F = 2\tfrac{1}{3} \text{ lb.}$$

Since on the circumference of an armature there may be hundreds of such wires, the majority of them simultaneously under the same influence, it is easy to understand that the combined tangential force, which in the case of an electric generator has to be overcome by the force of the driving engine, and in the case of an electromotor produces motion, may become very considerable.

In deducing the formula for the force

between a current and a magnetic field, we started from the simple case of a wire bent in the form of a circle. Let us use a coil of many turns, then the total volume of current flowing round the circle will be the product of the current and the number of turns. If we count the current in amperes, we may express the total volume of current as so many "ampere-turns." With i amperes and n turns the induction in the centre of the coil will now be

$$F = \frac{ni}{10} \frac{2\pi}{R}$$

Let us now suspend a small magnet in the centre of the coil; it ought to be small, so that both its poles may be considered as being simultaneously in the centre of the coil, since for this spot only is the formula for F valid. One end of the needle will be deflected to one side, and the other to the opposite side of the plane of the coil; in other words, the needle will try to set itself at right angles to the plane of the coil, and if there were no other forces acting on it, it would actually take up this position. Let the plane of the coil be north-south so that the needle, before a current is sent through the coil, lies in its

plane. On sending the current through the coil, a magnetic field is produced in the centre, the lines of force of which run east-west, that is to say, at right angles to the lines of force representing the horizontal component of terrestrial magnetism. The needle is now under the influence of two forces, one due to the earth trying to keep it in a north-south position, and the other due to the current in the coil trying to place it east-west. The true position it will actually adopt will be a compromise between these two tendencies. If the influence of the coil is equally strong with that of the earth, the needle will point north-west-south-east; it will have a deflection of 45°. If the current is made weaker, the deflection will diminish; if made stronger, it will increase. In this way, by observing the deflection of the needle, we can determine what is the strength of the current flowing through the coil. An instrument of this kind is called a "tangent galvanometer," the term "tangent" arising from the fact that the numerical ratio of the two forces acting at right angles is equal to the geometrical tangent of the angle of deflection.

If we were quite certain of the value of the horizontal component H of terrestrial magnet-

ism, an instrument of this kind could be used as a standard by which to calibrate, that is, mark the scale of commercial amperemeters, but in our electric age of tramways running in all directions, dynamos working in almost every building, and with steel joists used in the construction of buildings, the value of H in any given place is an uncertain and changing quantity. The tangent galvanometer can therefore not be considered as an absolute standard for current measurements, as it was considered by scientists two generations ago; but it may still be used for the measurement of very feeble currents if proper precautions be used. Since we must standardise the instrument in any case, there is no need to make the coil enormously large in comparison with the size of the needle; we can make both coil and needle very small, and use a great number of fine wire turns in the coil. By these means it is possible to produce an instrument which is capable of measuring the one-millionth part of an ampere or even less. It is obvious that with so delicate an instrument no material pointer to indicate the deflection can be used. The pointer is in fact weightless, being formed by a beam of light reflected from a little

mirror which is cemented on to the magnet needle. Such instruments are, therefore, called "mirror galvanometers." The light from a lamp is focussed on to the mirror and is from

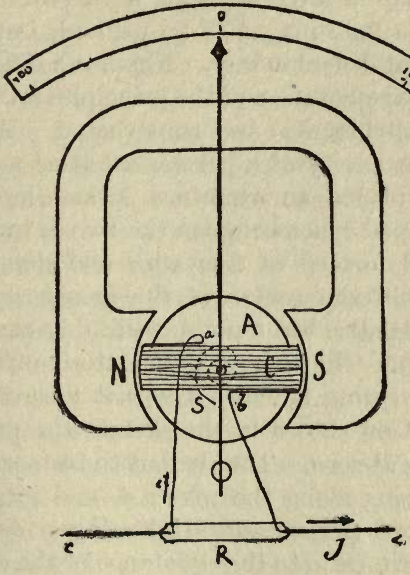

FIG. 8.

there reflected to a semi-transparent scale. On sending a current through the coil the spot of light on the scale is deflected and the amount of its displacement is proportional to the current. By sending a known current

through the coil and observing the resulting deflection, the instrument can be calibrated.

For the measurement of heavy currents such as are used in lighting or power work the dynamic force between a current and a magnetic field may also be utilised, but in a somewhat different way. Fig. 8 is a diagrammatic representation of the principles on which such instruments are constructed. Within the polar cavity of a permanent steel magnet N S is placed an armature A, and into the ring-shaped space between the two is inserted a coil C formed of fine wire and delicately pivoted in the centre of the armature. To the coil is attached a pointer suitably counterweighted. The coil is under the control of a spiral spring S which keeps it normally in the position shown in the sketch, the pointer standing at zero. The current to be measured I is flowing along the wire *c d*, and into this is inserted a resistance R having a definite and known ratio to the resistance of the coil C. According to this ratio more or less of the current I will be deflected and carried through the coil of the instrument by means of the attachment of flexible wires to the terminals *a b* of the coil, and it is obvious that by changing the resistance R one and the same

instrument may be made suitable for measuring currents of widely different magnitude. The deflected part i of the total current passes through the wires of the coil, and those parts of the winding which lie parallel to the surface of the cylindrical armature are subject to the influence of the induction in the air space between armature and poles. The dynamic force of the current is Bli, where l represents the total length of wire within the air space. The coil will thus be deflected against the controlling force of the spring, and since the deflection of a spring is proportional to the deflecting force, the excursion of the pointer over the scale is proportional to the current. The sense in which the pointer is deflected indicates at the same time the direction of the current.

Up to the present we have considered the dynamic action between a current and a magnetic field, but we have still to consider the dynamic action between two currents. For this purpose we go back to Biot-Savart's law and apply it to the case of a very long straight conductor. What is the induction at a small distance a from the axis of the wire? This problem can only be solved by the use of the calculus, and therefore it must

suffice to give the result. It is this: the force on unit pole placed a centimetres from a very long straight wire, through which the current I flows, is 2I divided by a; or in symbols, if I is given in amperes

$$B = \frac{I}{10}\frac{2}{a}$$

If we have two wires running side by side each lies in the field produced by the other, and thus there is a mechanical force drawing the wires together if the currents are in the same direction, and forcing them apart if the currents are in opposite directions. This is the explanation of the experiment described in the beginning of this chapter. Let us now inquire as to the magnitude of this force. We have found

$$F = \frac{I}{10} lB$$

and inserting the value of B we obtain the force in dynes

$$F = \left(\frac{I}{10}\right)^2 \frac{2l}{a}$$

or per meter run

$$F = \frac{2}{a} I^2 \text{ dynes.}$$

Two wires, each carrying 100 amperes and placed one cm. apart, will exert on each other a force of only 20 grams per meter run.

The relation between current strength in and induction round a long straight wire may be used to determine for any configuration of a magnetic system the exciting force in

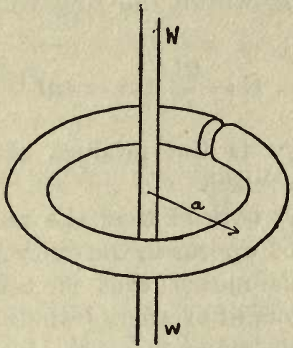

FIG. 9.

ampere-turns necessary to produce a desired magnetic flux. Let, in Fig. 9, W W be a portion of a very long straight wire, through which the current I is flowing. Assume at first that the medium surrounding the wire is air, and imagine a ring of this medium singled out for consideration. We wish to know the magnetic flux in this ring of mean

radius a and cross section A. The average induction over the cross section being $\frac{2I}{a}$, the flux is obviously

$$\Phi = A\,\frac{2I}{a}$$

To carry unit pole once round the wire along a path lying within the ring will represent the energy

$$E = \frac{2I}{a}\,2\pi a = 4\pi I$$

since energy is the product of force and distance travelled.

It will be noticed that the radius of the ring does not appear in the expression for the energy; this means that it takes exactly the same amount of energy whether we carry the unit pole round the wire at a short or a long radius. All we have to be careful about is that we go once completely round the wire so as to arrive again at the starting-point. Going round in one sense costs energy, going round in the other sense yields energy. Obviously the two amounts must be equal, otherwise we would have a perpetual motion machine, which is impossible. For the same reason it is not even necessary that the

journey should be performed in a circle concentric with the wire; any path costs or yields the same amount of energy.

In the case of a concentric ring of uniform section, in which the average induction H is produced by the current I, we have

$$\mathrm{H}l = 4\pi \mathrm{I}$$

where l is the length of path. The magnetic force acting throughout the length of the ring is therefore

$$\mathrm{H} = \frac{4\pi \mathrm{I}}{l}$$

Let us now replace the imaginary ring of air by a real ring of iron. This metal being very permeable to the passage of magnetic lines of force, we shall now have a vastly greater flux within the ring. The magnetising force is as before $4\pi \mathrm{I}/l$, but the induction resulting from this force has now increased some hundred, or thousandfold. It has increased by the amount corresponding to the coefficient of magnetic permeability μ. We thus get the mathematical expression for the induction

$$\mathrm{B} = \mu \frac{4\pi \mathrm{I}}{l}$$

The magnetising force, or magnetic force,

is $\frac{4\pi I}{l}$ and the induction is the product of magnetic force and permeability. The equation for B may also be written in the form

$$B = \frac{4\pi I}{\frac{l}{\mu}}$$

This is the same expression as we found for a ring of air, but with this difference, that the length of the ring instead of being l has now shrunk to a very much smaller value, namely $\frac{l}{\mu}$. If, then, we have a ring partly consisting of iron and partly of air, we may consider the whole of the magnetic circuit as consisting of air, but we must reduce the length of the part occupied by iron in the ratio of μ to l. To illustrate by reference to Fig. 9. Let the iron ring be interrupted by a small crevasse as shown. Let the length of the ring as far as it consists of iron be l_1, and let the width of the crevasse or air gap be l_2. The length of an equivalent ring consisting wholly of air will then be $\frac{l_1}{\mu} + l_2$ and the induction will be

$$B = \frac{4\pi I}{\frac{l_1}{\mu} + l_2}$$

The iron surfaces facing each other across the crevasse are the polar faces of an electromagnet excited by the current passing through the central wire W W. The shape of the magnet need not be a ring; all that counts in the problem is the length of the path in air and iron, the cross section of the magnetic circuit and the permeability of the particular iron used. In Fig. 9 the current is carried through the closed magnetic circuit by means of a very long straight wire. Needless to say, such an arrangement is quite impracticable. In order to use as little wire as possible we must wind the exciting coil close over the iron, and the question now arises, whether with a coil of any form wound over an iron core of any form, the relation between magnetic force and induction still holds good.

Let us first assume that we use instead of one straight and very long wire a circular coil of many turns. This is shown in section in Fig. 10. If all the n wires of this coil were concentrated in one circle of radius R the magnetic force in the centre O of the coil would be

$$F = \frac{2\pi ni}{R}$$

As we move to either side of O this force

very rapidly diminishes according to a certain mathematical relation, so that at the points A and B it is already inappreciable. The question we have to answer is: What energy is required to carry unit pole from a point infinitely distant on the right through the coil to a point at infinite distance on the

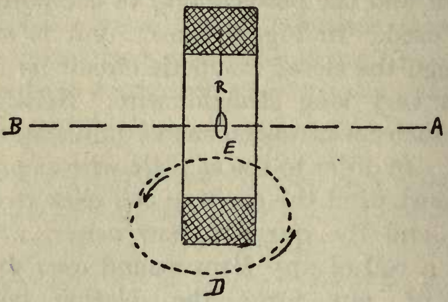

FIG. 10.

left? The mathematical investigation of this problem is best made by means of the calculus, but it would go beyond the scope of this book to give it in detail. For our purpose it must suffice to note the result. It is this: The energy required to carry unit of magnetic matter once through the coil is exactly the same as that required to carry it once round an infinitely long wire in which the same volume of current flows as in the coil. Thus

far the present case is covered by the previous argument. But we do not want to carry our unit pole from infinity on the right to infinity on the left; we want to carry it fairly close round the coil, say along the dotted line from D to E and round to D again. The dotted line forms the closed magnetic path, whilst the coil forms the electric path, both being interlinked. For reasons already stated, the exact shape of the path is immaterial. As long as we start and finish the journey at the same point, the same amount of energy is required to perform it. Let us then make the journey in the following way: Go from D a long way vertically downwards. This part of the journey costs no energy, since all the lines of force are crossed at right angles. Then go in a wide sweep to A. Also this part of the journey costs no energy, since it is made in a region where there is no force at all. It is only when we travel from A to O that we get into a region where we encounter opposing (or helping) forces. By passing from A through O to B we expend (or recover) the energy represented by $4\pi ni$, whilst the journey from B to D is again performed without recovery or expenditure of energy. If, then, the dotted line represents the magnetic

circuit consisting partly of iron and partly of air it will, as regards the relation between excitation and induction, be precisely in the same position as is the crevassed ring in Fig. 9, and the same formulæ apply. The excitation produced by a coil may be conveniently expressed by the product of amperes and turns, or "ampere-turns," and then we get for each part of the magnetic circuit a corresponding portion of the total ampere-turns. Let A_1, A_2, A_3 be the cross sections of the different parts of the magnetic circuit, l_1, l_2, l_3 the corresponding lengths, μ_1, μ_2, μ_3 the corresponding permeabilities, then the ampere-turns ni necessary to produce the flux Φ are given by the expression

$$ni = \frac{\Phi}{0 \cdot 4\,\pi}\left\{\frac{l_1}{A_1\mu_1} + \frac{l_2}{A_2\mu_2} + \frac{l_3}{A_3\mu_3}\right\}$$

This formula may also be written in a manner to bring in the induction in the different parts of the magnetic circuit. Remembering that induction is flux divided by cross section we have

$$B = \frac{\Phi}{A}$$

In dynamo machines, one part of the magnetic circuit is air. This is shown in the

diagrammatic sketch of part of a dynamo, Fig. 11. The dotted lines represent the way the lines of force flow between field magnet system and armature, and correspond to the dotted line E D E in Fig. 10. The hatched rectangles represent cross section through the magnetising coils as in Fig. 10. The physical identity between the real machine and the theoretical representation of the

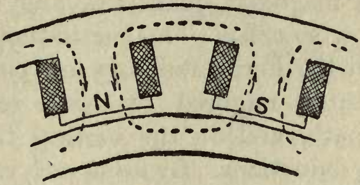

FIG. 11.

interlinking of the magnetic and electric circuits as represented by Fig. 10 will be seen at a glance. For air μ is unity. If we call B the induction in the air space between armature and polar faces, and l the combined length of the two air spaces that lie in the path of the magnetic flux, the formula for the exciting force in ampere-turns becomes

$$ni = 0{\cdot}8\ \mathrm{B}l + \frac{0{\cdot}8\ \mathrm{B}_1}{\mu_1} l_1 + \frac{0{\cdot}8\ \mathrm{B}_2}{\mu_2} l_2 + \ldots .$$

The permeability for any brand of iron is

not a constant, but depends on the degree to which the iron is magnetised. In such iron as is used in the construction of dynamo magnets it is fairly large at moderate induction, but becomes very much reduced at high induction. With an induction of about 14,000 it may be as much as 1,500, whilst with an induction of 20,000 it may be as low as 30 or even less. It is convenient to represent the magnetic quality of any brand of iron by a so-called "magnetisation curve," where on the horizontal axis are plotted the ampere-turns required by each centimetre of iron path, and on the vertical the corresponding inductions. By using such curves the above formula can be simplified as follows—

$$ni = 0{\cdot}8\,\mathrm{B}l + x_1 l_1 + x_2 l_2 + \ldots$$

The values of x are taken from the magnetisation curve and correspond to the different values of the induction which is found by dividing the flux by the cross section of the iron. By assuming different values for the total flux and calculating the ampere-turns for each case, we get a series of co-ordinate values of ni and Φ, which, plotted in a curve, characterise the machine as regards its magnetisation. Such a curve is therefore

called the characteristic of magnetisation, or the magnetising characteristic, or the "saturation curve" of the machine. The last name is not a very happy one, since there is no such thing as absolute saturation of a magnetic circuit. Moreover, even if we admit that there is in practice a saturation point, namely,

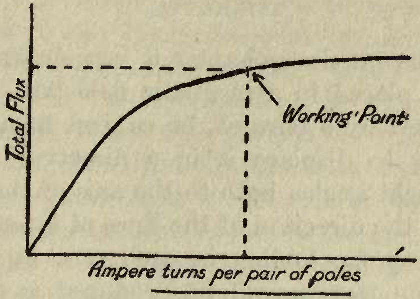

FIG. 12.

a point at which it becomes unprofitable to increase the excitation because the resulting increase in the flux is insignificant, the term is still misleading, because a machine is generally not worked at this so-called saturation point indicated by the characteristic, but at a somewhat lower degree of magnetisation.

Fig. 12 shows the general type of such a magnetisation curve and also approximately the position of the working point.

CHAPTER VII

THE DYNAMIC GENERATION OF ELECTRIC CURRENTS

In the previous chapter it was shown that a wire placed in a magnetic field will, when traversed by a current, be subject to a force tending to displace it in a direction which is at right angles both to the axis of the wire and to the direction of the lines of force. An easy way for finding in each case in which direction motion will be produced is to use the left hand for indicating the three quantities concerned, namely, direction of the magnetic force, current and motion. Set thumb, forefinger and middle finger at right angles to each other, and place the hand so that the forefinger points in the direction of the lines of force, and the central finger in the direction in which the current flows, then the thumb will indicate in which direction the wire will tend to displace itself.

If the displacement is allowed to take place,

it will be under the influence of the dynamic force of the current, and since force producing motion over a certain distance represents energy, it is obvious that the energy represented by the displacement must have come from the current. The rate at which the energy is produced, that is the energy yielded up by the moving wire in unit time, is called "power," and since a current can only give up power if it flows in opposition to an e.m.f., it follows that the movement of the wire across the lines of force has resulted in the generation of an e.m.f. in such a direction that it tends to diminish the strength of the current. We have here another example of Lenz's law mentioned on p. 50. To maintain the current at its old strength, we must add to the original e.m.f., which was required to overcome merely the ohmic resistance of the circuit, a further amount of e.m.f. to balance the opposing e.m.f. caused by the motion.

The direction of this counter e.m.f., or generally of any e.m.f. induced by the motion of a conductor in a magnetic field, may be determined by using the right hand as an indicator. Put thumb, forefinger and middle finger again into mutual quadrature, and place the hand so that the forefinger

points along the lines of force and the thumb along the direction of motion, then the central finger will indicate the direction in which an e.m.f. is induced. The power of the system represented by the moving wire may be expressed either mechanically as the product of force and velocity, or electrically as the product of current and counter e.m.f. Both must be equal, since in nature power can neither be created nor destroyed; it can only be transformed. By equating the two expressions for the energy we obtain the relation between the mechanical and the electrical unit of power. Engineers measure power in a unit called the horsepower, electricians measure it in a unit called the watt, so named after James Watt, or the kilowatt, which means 1000 watts. Power may, however, also be expressed in dyne-centimetres, or "ergs" per second, which is the way of expressing it in the absolute system of measurement. Using for the moment this system, we have the equation between mechanical and electrical power—

$$\mathrm{F}v = \mathrm{JE}, \text{ where } v \text{ is velocity,}$$

and since $\mathrm{F} = \mathrm{B}l\mathrm{J}$,

we have also $\mathrm{B}l\mathrm{J}v = \mathrm{JE}$,

and from this we find the law determining the

magnitude of the e.m.f. generated by electromagnetic induction. It is

$$E = Blv$$

The absolute unit of e.m.f. is that e.m.f. which is generated in a wire one centimetre long, when moved with a velocity of one centimetre per second at right angles across the lines of a magnetic field in which the induction is one electromagnetic unit. The unit of e.m.f. thus defined is inconveniently small for practical work. A much larger unit, namely the "volt," is used in practice, and its magnitude is $100,000,000 = 10^8$ as large. On the other hand, the electromagnetic unit of current is 10 times as large as the practical unit, namely the ampere. If, then, we wish to pass from the absolute system of measurement of power to the practical system, we must use the reducing factor 100,000,000 divided by 10, or $10,000,000 = 10^7$. We thus find that the power represented by 10 million dyne-centimetres per second is equal to the power represented by one watt. The energy represented by 10 million ergs is equal to the energy represented by one watt second or one "Toule."

A similar reduction can be made when passing from the absolute system of power

measurement to the practical system used by mechanical engineers. The kilogram is equivalent to 981,000 dynes, and one kilogram-metre is represented by 98,100,000 ergs. To produce 10,000,000 ergs, which is equivalent to one watt second, only $\frac{10}{98{\cdot}1} = 0{\cdot}102$ kgm. of mechanical energy is required; or one kgm. per second of mechanical power is the same as 9·81 watts of electrical power. Since the English horsepower is 550 ft.-lb. per second, or 76 kgm. per second, the electrical equivalent of one hp. is 746 watts. The output of electric motors is generally stated in hp., that of electric generators in kw.

The discovery of electromagnetic induction as a source of current is due to Faraday. He first enunciated the fundamental fact that if a wire cuts across lines of magnetic force, an e.m.f. is induced in the wire. This e.m.f. will produce a current, if the ends of the wire are joined up by some other conductor. We have thus a closed electric circuit, of which a particular part, namely the wire under consideration, is cutting through lines of force; and we also have a magnetic circuit interlinked with the electric circuit. That interlinking must take place is obvious. As long

as there is any cutting of lines, some lines must be inside and some outside the electric circuit; in fact the cutting is necessarily accompanied by the transfer of lines from the outside to the inside of the electric circuit or vice versa. Further, lines of force must be conceived as curves closed in themselves, and therefore all the lines passing inside the electric circuit form a kind of magnetic ring which is interlinked with the ring formed by the electric circuit. If, then, the wire cuts through some of these lines, the amount of interlinkage is altered, and we may thus also define the electromagnetic induction of an e.m.f. as a process of altering the interlinkage of the two circuits. In the expression for E given above, namely—

$$E = Blv$$

the product of induction, length of conductor and velocity is obviously nothing else than the magnetic flux added to or withdrawn from the electric circuit in unit time, that is the rate at which the interlinked flux changes with time. We may, therefore, also write for the e.m.f. in absolute units produced in a coil of one turn—

$$E = \frac{d\Phi}{dt}$$

$d\Phi$ being the very small change of flux that occurs in the very small time dt.

If the coil has n turns the e.m.f. induced will

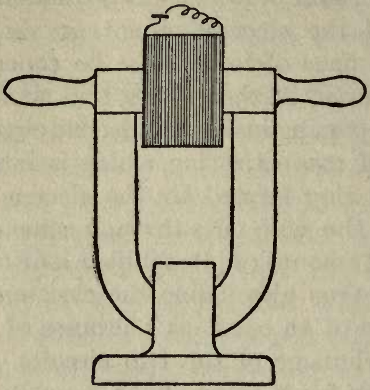

Fig. 13.

be n times as great, and its value expressed in volts will be—

$$E = n\frac{d\Phi}{dt}10^{-8}$$

That an e.m.f. is produced by the change of flux passing through a coil was proved experimentally by Faraday in the following way. Fig. 13 represents a permanent horseshoe magnet securely fastened to the table. Its armature or keeper of soft iron is provided with a coil of many turns of fine wire. One end of

this coil is furnished with a little metal plate, and the other end of the wire rests loosely on this plate. If the keeper is placed over the poles, the flux emanating from them passes through the coil. If the keeper is taken away, the lines which previously passed through its interior vanish. By drawing the keeper away slowly the rate at which the lines vanish is slow, and consequently no very great e.m.f. will be induced in the coil, but if we accelerate this rate a fairly high e.m.f. may be induced. In order that it may be possible to tear off the keeper very quickly, it is provided with handles. By giving these handles a blow with both hands from below, the keeper comes off with a jerk, and the rate at which the flux diminishes is great, hence a large e.m.f. is induced. At the same time, as a consequence of the jerky motion, the point of the loose wire resting on the plate is caused to separate a little and thus an arc is produced as evidence that a current is circulating through the coil.

Some of the ignition apparatus used in motor cars and some mine exploders are constructed on the same principle. Faraday's plate and loose wire are replaced by a properly constructed sparking plug, but the spark is produced in the same way as in the original

experiment, namely, by the sudden change of flux through a coil, the terminals of which are connected to the plug. Electromagnetic induction is also the working principle of all dynamo machines, but here we do not want to produce sparks at given times, but a sustained electric current flowing under a definite and steadily maintained e.m.f. Hence coils must go into and come out of action in regular rotation, and this condition is fulfilled by the part in the dynamo called the armature.

Let, in Fig. 14, A be a cylindrical piece of iron capable of revolving between the poles N S; and let this cylinder be wound with a coil C_1, C_2, the wires passing across the face and along the sides of the cylinder. One end of this coil is attached to an insulated metal ring R_1, and the other to a similar ring R_2. Metal springs B_1 and B_2, technically termed "brushes," press against these rings for the purpose of maintaining electrical continuity between the revolving coil and the fixed points of attachment of the external circuit, which by way of example we may take to contain an incandescent lamp. In the position shown, the full flux from the magnets passes through the coil, but no e.m.f. is generated, because at that particular moment

there is no change in the flux if the armature is slightly rotated to one side or the other. In other words, the rate of change of flux through the coil is zero. Now imagine the armature

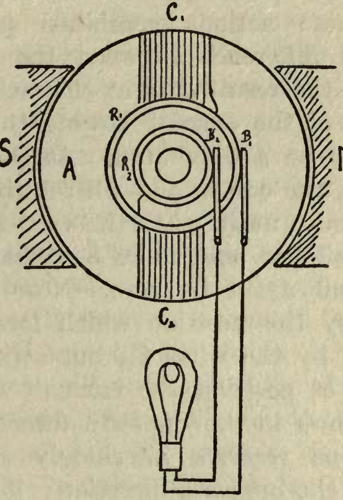

Fig. 14.

revolving clockwise, so that the side of the coil marked C_1 comes opposite the N pole. Now the rate at which the lines of force emanating from that pole are cut is a maximum, and at the same time the flux through the coil is zero. At that moment a maximum of e.m.f. is induced in the wires of the coil on

both sides. By the right-hand rule stated on p. 171 we find that in the wires C_1 the direction of the e.m.f. will be downwards, or away from the observer, whilst in the wires C_2 it will be upwards, or towards the observer. Both these actions combined produce a potential difference between the rings R_1, R_2, with the result that at that moment the strength of the current flowing through the lamp will be a maximum. As the rotation proceeds, the e.m.f., and with it the current, will diminish until, when the vertical position of the coil has once more been reached, the e.m.f. will again be zero. Now the wires C_1 occupy the position which formerly was occupied by the wires C_2, but owing to this reversal of position the current which now starts, flows in the opposite direction. The lamp thus receives alternately current in one and the opposite direction; it is lighted with an alternating current. We have here a simple form of dynamo machine producing alternating current. The rate at which the direction of the current alternates is technically termed the "frequency." In a machine having two poles it coincides with the numbers of complete revolutions performed in one second.

Twice during each complete period the lamp receives alternately a maximum of current and no current at all. Will this produce a disagreeable flicker ? The answer to this question depends on two things; first the frequency and then the thermal storage capacity of the lamp filament. The light is due to the high temperature of the metallic filament, and that is due to the current. A strong current produces more light than a weak one, but the emission of light does not instantly follow the variation in current strength. Time is required for heating and for cooling, and provided the intervals between heating are sufficiently short as compared to the heat which the lamp can radiate in the time, its temperature will not materially change and there will be no flicker. Obviously the thinner the filament and the greater its radiating power, the higher must be the frequency at which flickering is no longer noticeable. There is also a personal element in the observation of flickering; some persons observe it sooner and feel it more unpleasantly than others. From experiments I have made with various lamps and assisted by various observers, I found that at a frequency of 25 no observer could detect flickering when

carbon lamps were tried, but some detected, or thought they detected, flickering when metallic filament lamps were tried. At slightly less than 25 frequency the majority of observers detected flickering. We may thus take 25 as a yet permissible lower limit for the frequency if the current is to be used in incandescent lighting. With arc lighting the lowest frequency permissible is 40. As a general rule lighting current is supplied at a frequency of 50. To get such a frequency with a machine built on the principles shown in Fig. 14 would require driving it at a speed of 3000 revolutions a minute. Such a speed is too high for ordinary steam engines, athough it is well within the range of steam turbines. Apart, however, from the question of driving, it is mechanically and electrically wrong to subject a coil, which must be highly insulated, to so high a speed. High speed means great centrifugal forces, and that means great mechanical stress on the insulating material. Such stresses should be avoided as far as possible. For this reason the mechanical arrangement of field magnet and armature is reversed in modern machines. It is the magnetic field which is caused to rotate, and then it is possible to keep the armature

stationary. The objection against rotating coils does not apply to the exciting coils of the field magnet system with anything like the same weight as to the armature winding. In the first place, the field coils need only be insulated for some hundreds, but not thousands of volts, and in the second place they can be

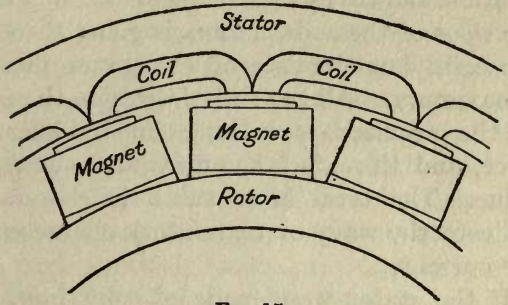

FIG. 15.

made of a very compact and simple shape, and this renders a safe mechanical attachment possible.

Fig. 15 shows diagrammatically the general principles on which modern alternating current dynamos are constructed. The coils in which the alternating e.m.f. is generated are carried on the inner surface of a cylindrical armature, technically termed the "stator" because it is a fixed part. The magnet system is the

revolving part or "rotor," and may have two or any even number of poles. In Fig. 15 it is assumed that the rotor is multipolar, so that the desired frequency may be obtained with a moderate speed of revolution. The action of the machine is the same as already explained with reference to Fig. 14. In the position shown the polar faces are opposite the sides of the coils, no flux is going through the coils, but the rate of change of flux is a maximum. All the active wires on the face of the armature are being cut by lines of force, and the e.m.f. has maximum, or crest value. The term crest value is chosen to indicate the wavy or undulatory character of the current.

If the stator were made of solid iron, an e.m.f. would be induced not only in the wires, where we desire to have it, but also in the mass of the iron, where we do not desire it. We do not desire to have currents flowing in the body of the stator iron, because whenever a current flows through a conductor, be it a wire or a lump of iron, the material of the conductor gets heated, and that heat has to be paid for in the shape of some extra power which the driving engine is called on to supply. This would be pure waste, and to avoid such

waste taking place, it is necessary to prevent currents circulating in the mass of the stator iron.

We cannot avoid an e.m.f. being generated in the iron as well as in the copper conductors, since both are side by side; but we can prevent this e.m.f. from producing a current, and this is done by interrupting its path. This means subdividing the iron into thin plates, which are insulated from each other by varnish or paper. This does not interfere with the flow of magnetism, for, as we have seen, there is always quadrature, that is, a right-angular relation between flux and the direction in which an e.m.f. is induced. Hence an insulating surface which interrupts electrical continuity is parallel to the direction of the magnetic flux, and apart from slightly reducing the available cross section for the transmission of the lines of force, does not interfere with the magnetic circuit. It may be mentioned that not only in such dynamos, but in all electrical machinery and apparatus where there is either a change of flux or a progression of flux through iron, the iron must be laminated.

It has been shown in the previous chapter that very considerable forces act on armature

wires. Their safe mechanical support thus becomes a matter of first importance. We cannot stick the wires on the very surface of the armature, but we can place them into slots or tunnels close to the surface. In this way the wires are securely held and are relieved from mechanical stress, which is now taken by the iron bridges between the wires and not by the wires themselves. The slots or tunnels are lined with tubes of insulating material, and thus complete protection of the winding, both in a mechanical and electrical sense, is secured.

It will be noticed that in the alternator diagrammatically shown in Fig. 15 more than half the inner surface of the stator is left free from winding. This free space may be utilised for a second winding placed exactly midway into the free space left by the first winding. Let us call the two systems of winding A and B. If the poles are in such a position that the e.m.f. in the A winding is zero, they are exactly opposite the wires of the B winding, and generate in these wires crest value of e.m.f. Conversely if, a moment later, the e.m.f. of the B winding is zero, that of the A winding has crest value. We have thus two waves of e.m.f. and current running

through the machine. These waves are relatively to each other displaced by a quarter period. A machine of this kind, which from the same armature gives two independent currents displaced by a quarter period, is called a "two-phaser" or a "two-phase machine." We may also provide the armature with three distinct phase windings, each displaced against the others by one-third of a full period, or 120 degrees. Such a machine is called a "three-phaser" or "three-phase machine." The use of three-phase current results in certain technical and financial advantages in the supply of electricity, and it is on this account that most modern electricity works, if they use alternating current at all, use it in the shape of three-phase current.

But suppose an electricity works does not want to supply alternating current to its customers, but continuous current. What sort of machinery will it have to use in this case? If we wish to produce continuous, that is uni-directed, current by electromagnetic induction, we must obviously add to our machine some organ which reverses the current in every second half-wave. But this is not enough. Even after we have reversed every

second half-wave, the current will be pulsating between zero and a maximum. It is true, the maximum will always have the same sign corresponding with the general sense of flow, but the flow will be extremely irregular, and in some respects, such as the question of flickering, no better than an alternating current. The alteration we need make to get out of the machine shown in Fig. 14 a uni-directed current, or, as it is technically termed, a "direct current" (abbreviation "DC"), is simple enough. We need only, as shown in Fig. 16, replace the two whole rings by one ring split into two halves R_1 R_2, which are insulated from each other and connected respectively to the two ends of the coil. In Fig. 16 the coil is shown as consisting of only a single turn. This is done to avoid a complicated diagram. In reality the coil would have a large number of turns. The brushes are placed right and left on a horizontal diameter. By applying the right-hand rule it will be seen that with clockwise rotation of the armature, brush B_1 is always the negative and B_2 always the positive brush. The machine therefore gives DC, but a strongly pulsating DC.

In order to smooth out the pulsation to an

extent which will make the current really continuous, a special method of arranging the winding and a special organ, namely the "commutator," is required. In a sense the two half-rings of Fig. 16 are a commutator, for they are instrumental in commutating the

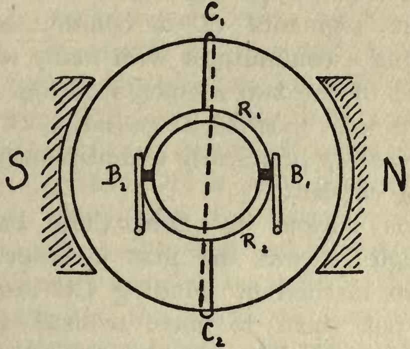

Fig. 16.

AC into a pulsating DC. But this commutator has only two segments, hence its imperfect action. The merit of having improved both method of winding and commutator, so that the machine may give a steady DC, belongs to Pacinotti, who was Professor of Physics in the Turin University. He published in 1864 a description of a continuous current dynamo machine, which he had constructed

four years previously for purely scientific laboratory experiments. The organ in which the continuous current was generated, consisted of an iron ring provided with a winding of copper wire in the form of a continuous spiral closed in itself. At even intervals connections were brought out from this spiral to the segments of a commutator. By adopting a commutator with many segments instead of the two segments of Fig. 16, the current loses most of its pulsating character, and becomes practically a continuous, evenly flowing current.

It is curious to note that Pacinotti, although he was the first inventor of the modern method of winding DC armatures, does not seem to have realised the immense practical importance of his invention; at any rate he made no attempt to utilise it practically. In this respect there is some similarity between Pacinotti and another great Italian physicist, namely Galileo Ferraris, who in 1887 discovered a method by which rotative motion could be obtained by the combined action of two-phase or three-phase currents. Ferraris not only failed to see the importance of his discovery for the production of motive power, but he went even

so far as to throw doubt upon it; for in his first publication he said that his discovery might possibly have some use in the construction of electricity meters, but that it would probably be useless for electric motors. Yet more than half the motive power produced electrically nowadays is produced in machines in which the discovery made by Ferraris is utilised. Pacinotti was content to utilise his invention for his own scientific experiments, but he did not apply it for industrial purposes. This was done by Zenobe Theophil Gramme in 1869. It is very probable that Gramme, who at the time was employed as pattern-maker in an electrical manufacturing firm, had never heard of Pacinotti's invention. He re-invented the spiral winding and the many-part commutator; and recognising the practical importance of this invention he patented it in 1869. Hence this type of armature winding is called a "Gramme winding," or also a "Gramme Ring" or a "Ring Winding." It is diagrammatically represented in Fig. 17. S N are the poles of the field-magnet system so shaped as to produce a polar cavity in which the armature revolves. This consists of an iron ring R wound with insulated copper wire, the winding

forming a spiral, Sp, closed in itself. At even intervals this winding is tapped by conductors which connect it to the segments of the commutator C. Let the armature revolve clockwise, as shown by the arrow. If the reader will apply the right-hand rule

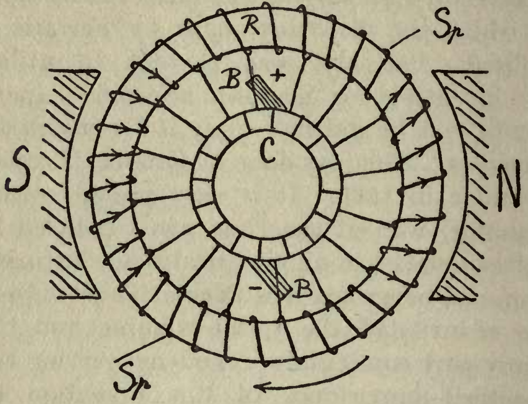

FIG. 17.

given on p. 171 he will find that in all those parts of the continuous spiral, which lie immediately under the N pole at any moment, an e.m.f. directed as shown by the arrows will be generated. The same applies to those parts of the spiral which lie within the sphere of influence of the S pole. By following the winding in the direction of

these arrows we find that these e.m.f. impulses all add up in the right sense, so as to push current out at the positive brush B shown at the top; and to draw current into the armature at the negative brush B shown at the bottom of the figure. By joining these brushes to the terminals of some external circuit, a continuous current in this circuit is therefore obtained.

It should be noted that only those portions of the wire which are between the ring and the poles are active. Those parts of the wire which pass through the inside of the ring contribute nothing to the generation of an e.m.f., because the ring itself shields them from the influence of the poles; and if this shielding were not present, the influence would be the wrong way. Thus the inside part of the spiral is useless and even harmful, for it increases the resistance and it magnetises the inside of the ring. This magnetisation, being at right angles to the magnetisation originally produced by the field magnets, does not directly interfere with the working of the machine, but it has an indirect influence. The shaft and the attachment of the ring to it must be of metal, and this metal, in cutting through the lines of

force of the internal field, becomes itself the seat of e.m.f.'s which produce what may be called parasitic, that is useless, currents in these metal masses, producing heat and wasting power. The mechanical attachment between ring and shaft is also difficult, as the space is limited and most of it is wanted for the accommodation of the winding itself. All these difficulties would vanish if it were possible to avoid passing the wire through the interior of the ring. In this case we need not use a ring at all, but we might use a solid drum, or at least a drum of iron made up of thin plates, but filling as much of the space as may be necessary to carry the magnetic flux across from one pole-piece to the other.

It is the merit of a German engineer, namely von Hefner Alteneck, to have made these improvements possible by the invention of what is technically known as "drum winding." The wires are left on the outside of the ring as shown in Fig. 17, but instead of taking the second half of each turn through the ring, it is taken across the end face of the drum and then down its outer surface. The connections to the commutator are tapped off from every second wire. Thus a drum

containing 100 wires would have a 50 part commutator, and every second wire would be connected to this commutator. Instead of single wires, groups of wires made up into coils may be used. It will be obvious that the e.m.f. generated in the armature will be the greater the greater the number of wires on the drum. If then a high e.m.f. is required, the number of wires, counted all round the armature, may easily become so great, that if we have to provide a segment in the commutator for every second wire, the commutator would have to be made up of exceedingly thin segments. For obvious reasons there is a limit to the decrease in the thickness of commutator segments, so that the rule, that one segment must be provided for every two wires, cannot always be adhered to. This difficulty may be overcome by grouping the wires in coils. The number of segments need then only be as large as the number of coils, that is one half the number of coil sides. Each coil side then takes the place of one individual wire.

There is in connection with drum winding a purely mechanical difficulty which must be mentioned. I said above that the connection between the front end of one wire to the front

end of the wire diametrically opposite is taken across the face of the drum. It is obviously impossible to take it straight across, for on the one side there is the shaft in the way and on the other the commutator, the diameter of which may be half that of the drum or even more. Thus the space at both drum-heads is not free, and to take the connections across we must so shape them as to avoid these central obstructions and at the same time not interfere with each other. This is a purely mechanical problem, and has been solved in various ways. As it has only interest for the professional designer of dynamos the various solutions need not be detailed here, but it may be pointed out that the mechanical difficulties of arranging the end connections become less serious when drum winding is applied to a machine having more than two poles. In a four-pole machine the end connection need only span a quarter of the circumference; and in a six-pole machine only one-sixth. Thus to avoid commutator and shaft is an easy matter, whilst avoiding mutual interference of end connections is also easier, since their length is reduced and there are fewer of them crossing each other. This is one of the reasons why modern

machines are generally made with four or more poles.

Another feature of modern machines is the secure fastening of the active wires. Fig. 17 is merely a diagrammatic representation to illustrate a principle; it is not a drawing of a real machine. If the wire were simply wound over the outside of a smooth drum it would be very difficult to hold it securely in place. Not only would the wire bulge out

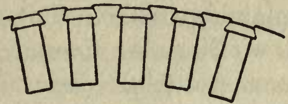

FIG. 18.

by reason of centrifugal force, but the magnetic drag on the wire would displace it along the circumference. In modern machines the wires or coil sides, as the case may be, are secured in position by being placed in slots, as shown in Fig. 18. The core of the armature consists of thin iron plates which are slotted on special stamping machines. In building up the core, the plates are so laid one upon the other that all the slots register properly and form grooves parallel to the axis, into which the wires are

placed. To prevent the wires from being thrown out by the action of centrifugal force the groove is closed by the insertion of dovetailed wooden wedges. The reason for using thin plates instead of a solid body for the core of the armature is to prevent the creation of parasitic currents in the mass of the iron. This point has already been discussed earlier in this chapter when dealing with alternating current machines, and the reasoning then applied remains valid also for D C machines.

When explaining the action of an armature with closed winding, we assumed the existence of a magnetic field emanating from the poles N S without specifying how this field is produced. We might produce it by using some source of electricity such as a primary or a storage battery to excite the field magnets, but this would be a cumbersome method, since it would make the action of the machine dependent on some other source of electric supply. It is possible to dispense with this extraneous original source of exciting current by letting the machine excite itself. Imagine the current coming out of the brush marked positive in Fig. 17 not led straight away into the external circuit, but passed first through the magnetising coils of the field system.

Before the current flows there is no magnetism in this system, or, to speak more correctly, there is but a very feeble magnetisation. It is next to impossible to have any piece of iron absolutely devoid of any trace of magnetism. The very act of machining the iron during the process of manufacture is sufficient to produce some feeble magnetisation. This fact the reader may test for himself in a very simple manner. Let him take an ordinary kitchen poker, hold it north-south and twist it with his hands. If he then approaches one end to a compass needle and then the other, he will find that the poker has become a feeble magnet. By reversing the position and twisting again he will be able to reverse the polarity, thus proving that it is the feeble influence of the earth's magnetism which, combined with the mechanical stress on the molecules due to the twisting, has produced the magnetisation. The material of the field-magnet undergoes during the process of being worked into shape a good deal of mechanical stressing, and hence becomes magnetic. There is thus, to start with, some feeble magnetisation in the system. The corresponding e.m.f. produced at the brushes is also correspondingly feeble, but if the

current is led round the exciting coils in the proper sense, this feeble current will slightly increase the original magnetisation, this in turn will produce a slightly greater e.m.f., this again will strengthen the field, and so on until the machine is fully excited. We have here the principle of "self-excitation." Once the machine has been excited there remains what may be called "residual magnetism," and the process of self-exciting takes place more readily. A machine in which the whole of the armature current is led round the exciting coils is called a "series machine," which term is chosen to indicate, that the exciting coils are coupled in series with the external circuit. Since the whole of the current is used for excitation a moderate number of turns in the series coils suffices. But these must be of sufficiently stout wire to carry the whole of the current.

Now let us wind these coils with much finer wire, but, to make up for the lesser current which such wire can take, let us use a much larger number of turns. The current which we wish to have in the external circuit is much too large to be carried by this fine wire coil, and we must therefore feed it directly from the brushes. The exciting coil

forms an electrical shunt to the external circuit, and machines of this kind are therefore called "shunt machines."

Some of the e.m.f. induced in the armature is necessarily lost in overcoming the internal resistance of the machine, so that the e.m.f. available at the terminals is a little smaller than the induced e.m.f., the difference being the greater, the greater is the current the machine is called upon to furnish. Since the excitation of a shunt machine is proportional to the potential difference at its brushes, and since this decreases with the external current, such a machine cannot give an absolutely constant voltage. Its voltage will slightly drop with an increase of external current. On the other hand, a series machine is excited by the external current, and if this increases the excitation also increases, so that within certain limits the voltage rises with the external current. We have thus in the two types contradictory working conditions. If the machine is "series excited," the terminal e.m.f. rises with an increase of load; if it is "shunt excited" the terminal e.m.f. drops with an increase of load. If then we combine these two methods of excitation, that is, if we magnetise the field system both by a shunt

and a series winding, we can so proportion these coils that the terminal voltage shall remain sensibly the same over a large range of external load. Machines of this kind are called "compound machines."

Any dynamo may be used as an electric motor. The type most generally used is the shunt machine, since its speed, even under large variations of mechanical load, remains fairly constant.

CHAPTER VIII

ALTERNATING CURRENTS

When we speak of a current flowing along a wire, we conceive this process as the transfer of a something called electricity from one end of the wire to the other. If by some means the potential of the near end of the wire can be kept higher than that at the far end, the direction of flow will be outwards; in the opposite case (near end at a lower potential than far end), it will be inwards. This mental picture of an electric current. is obviously incomplete. To say that the near, or home end of a wire is raised to a higher potential than the far end, is the same thing as to say that we discharge positive electricity, say from a voltaic cell, into the home end; but we have seen that whenever a certain quantity of positive electricity is generated, an equal quantity of negative electricity is also generated. Unless this can flow away no positive electricity can flow into the home end of the

wire. Thus we see that we must have a second wire connected to the negative pole at the home end, and to the first wire at the far end. With one wire alone we cannot transmit electricity from one point in space to another. We must always have two wires, one outgoing, the other returning. We must, in fact, always have a closed loop. The loop may be quite narrow and many miles long, but it must be a closed circuit. Since the object of sending electricity over a certain distance is not to merely cause a current to flow in the two wires, but to do some useful work at the far end, we must not join the two wires at the far end directly, but must make the connection by way of some apparatus in which the electric current is to be utilised. At one end of our electric line consisting of two wires we have the apparatus which generates electricity, at the other, we have the apparatus which utilises it.

Let the generator at the home end be a dynamo, and the apparatus at the far end a lamp. Since the current in the outgoing wire is always exactly of the same strength as that in the incoming wire, there is no accumulation of electricity in the lamp; there is only a conversion of the

energy represented by the product of current and drop of e.m.f. on passing the lamp into heat energy, some of which appears as light waves. As far as this conversion is concerned, the direction in which the current flows is quite immaterial. If the current always flows the same way, we call it a continuous or direct current (abbreviation D.C.). If the current changes its direction periodically, we call it an alternating current (abbreviation A.C.).

When a current changes its direction or sense of flow, there must necessarily be a moment when the flow is neither in one nor in the other direction; in other words, for a moment there is no current at all. We say the current strength passes from a positive value through zero to a negative value. Alternating currents are produced by machines of the type shown in Fig. 15. As the poles sweep by the active wires the induced e.m.f., and therefore also the resultant current, changes gradually, and if we represent this change graphically by plotting time on the horizontal and either e.m.f. or current on the vertical, we get a wavy line as shown in Fig. 19. The distance *a* to *b* is called the periodic time of the current, and the greatest amplitude of the wave is called the " crest value " of the

current. A complete wave from *a* to *b* is called a " cycle " or " period," and the number of cycles occurring in a second is called the " periodicity " or " frequency " of the current. In most electricity works supplying current for lighting the frequency is 50; if the supply is mainly for motive power the frequency is lower, generally 25, and for electric railways a

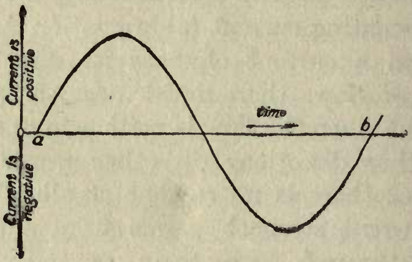

FIG. 19.

still lower standard is likely to be generally accepted.

It will be obvious that, in electric working of main lines of railways, some agreement between the different countries as to a standard frequency is highly desirable, for a change of engine when passing a frontier would be a useless complication in the service. A beginning in the direction of internationally standardising the frequency for electric

railways has already been made by Prussia, Baden and Bavaria, who have agreed on $16\frac{2}{3}$. This figure has been arrived at by the consideration that in many cases the possibility of interchanging power between a railway and general supply might be convenient. Machinery for converting frequency can be built and worked most economically if the ratio of conversion is given by whole numbers, such as 1 to 2 or 1 to 3. Since general supply systems are mostly working with a frequency of 50, and the conversion to half that frequency would still leave the frequency a little too high for the attainment of best working conditions in railway propulsion, a converting ratio of 1 to 3 has been adopted by the States abovementioned. This gives for the railway a frequency of $16\frac{2}{3}$. Italy and Switzerland have adopted a standard of 15, but with a latitude of 10 per cent. up or down, so that at the higher figure they come very nearly into line with the German standard, whilst at the lower figure the Swiss railways have the possibility of linking up, by means of frequency transformers, with some existing works for general supply, whose frequency is in some cases as low as 42.

Whatever may be the frequency adopted

in any particular case, it will be obvious that the power of an A.C. must depend on its e.m.f. and strength. But how shall we define either, since both are continuously varying? Shall we, in defining the strength of an A.C., give its crest value as so many amperes, or shall we give some smaller value? Apparently the simplest plan would be to give the crest value, but this would not be a true measure. If we take by way of illustration the case of a lamp lighted by passing an A.C. through the filament, we have seen that twice during each cycle there is a moment when the current is zero. At those times the lamp receives no power, whilst at the times when the current has crest value it receives a maximum of power. The average power absorbed by the lamp must therefore be something between this maximum power and zero. If, then, we define the strength of the current by stating its crest value, we overestimate it. The proper basis for estimating the strength of an A.C. is obviously that of equal effect produced by a D.C., and we may thus speak of the "effective" (sometimes also called the "virtual") value of an A.C. With modern A.C. machines the shape of the e.m.f. and current curve shown in Fig. 19 closely approaches a

sine curve. To draw such a curve we may proceed as follows: Draw, as shown in Fig. 20, a circle with a radius equal to the crest value of the current in any convenient scale. Divide out the circle into a number of equal parts, and divide the line *a b* in Fig. 19 into the same number of equal parts. Now let the radius rotate, and every time it comes to one of

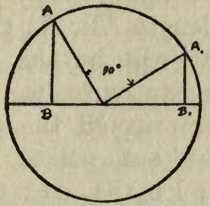

FIG. 20.

the points marked out on the circle, measure the height of this point over the horizontal, and plot this height over the horizontal in Fig. 19 at the corresponding division point. By the time we have once gone round the circle, we shall have obtained, in Fig. 19, all the points of the sine curve between *a* and *b* which are required to draw this curve. The rotating radius is called a "vector," in this case a "current vector," since its projection on a vertical line gives at any moment during its

revolution the instantaneous value of the current. Thus the value of the A.C. corresponding to the vector position A is AB. The instantaneous value of the power at that moment is the product of the current AB into the e.m.f. over the lamp terminals at that moment. Now this e.m.f. is, by Ohm's law, the product of current and resistance, so that the instantaneous power is proportional to the square of the length AB. If, then, we wish to ascertain what will be the average power during a complete cycle, we would have to draw the vector in all the positions given by the marked-out points on the circle, square all the lengths, add the squares up, and divide by the number of positions to which we have applied this arithmetical process. Taking the square root of this figure gives a length, and measuring this length with the ampere scale which we originally used in determining the length of the vector current, we get the effective current. To actually carry out such a calculation would be very laborious; fortunately we can avoid this mathematical drudgery by making use of the well-known Pythagorean axiom that the sum of the squares of the kathetes in a rectangular triangle is equal to the square of the

hypotenuse. Let us assume that instead of making the calculation for one vector only, we make it simultaneously for two, such as A and A_1, situate at right angles to each other. Since we count each vector twice over, the result will also be twice the true value. We have now to form the sum of AB^2 and A_1B^2, but by the axiom just mentioned, this is always equal to the square of the vector itself. Since this is the same for all positions, the mean is the same as each part, but since we counted each vector twice, the mean is twice the real value. The square of the effective value of the current is therefore one-half of the square of the crest value, or the effective value is found by dividing the crest value by the square root of 2. This is 1·4, and 1 divided by 1·4 is 0·71. We thus find that the effective value of an A.C. is 71 per cent. of its crest value. The same relation applies of course also to the e.m.f. The same reasoning which has here been applied when discussing the passage of the A.C. through the lamp, also applies to its passage through any measuring instrument adapted for A.C. Amperemeters and voltmeters give the effective values, not the crest values. In the case of an incandescent lamp, the product of the current shown on such an

amperemeter, with the e.m.f. shown on such a voltmeter, gives the true power absorbed by the lamp.

If the receiving apparatus is an electric motor this simple relation does not necessarily hold good. The product of current and pressure may be the true power, but it is not necessarily the true power. It will give the true power if the crest values of current and pressure occur at the same moment, but if there is a time displacement between their occurrence, then the true power is smaller than the product of current and pressure. Now why should there be a time displacement? The reason is this. In a motor there are coils of wire embedded in iron and the current has to pass through these coils. The current produces thus a flux of magnetic lines which grow and diminish and reverse their direction with the corresponding changes in the current strength. A coil interlinked with a changing magnetic flux becomes, as was shown, the seat of an e.m.f. When the current passes through its crest value the rate of change, and therefore the e.m.f., is zero; when the current passes through zero value its rate of change is a maximum, and at those times the self-induced e.m.f. is also a maximum.

We thus find that in point of time the e.m.f. induced by the current in its own circuit does not coincide with the current, but lags by a quarter of a period behind the current. The e.m.f. impressed on the motor must therefore not only have a component which is co-phasal with the current and which gives the power, but also a component equal and

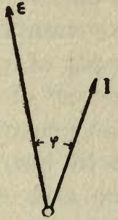

FIG. 21.

opposite to that which the current induces itself, and which therefore in point of time must lead over the current. The vector of the impressed e.m.f. and of the resulting current are no longer co-phasal, but form an angle φ as shown in Fig. 21, where OE represents the e.m.f. vector and OI the current vector. The component of OE in the direction of the current is OE $\cos\varphi$, and the true power is therefore

$$P = ei \cos \varphi$$

Cos φ is called the power factor, and it is the aim of the designer to so arrange the circuits of a machine as to make the power factor as near unity as possible. A low power factor is objectionable because an unduly large current or an unduly large voltage is required to produce a given amount of power. This means greater bulk and cost of machinery, and also stouter cables for the transmission of the current from the generating station to the places of consumption. The average power factor of electricity works supplying alternating currents is 0·8 or even less. This is due to the supply of current to electric motors and arc lamps. Small motors may have a power factor as low as 60 per cent., large motors may have a power factor as high as 90 per cent., and with some special types even unity may be reached, but as the bulk of the supply is taken in small and moderate-sized motors, an average of 0·8 is as high as can reasonably be expected.

The current delivered at the places of consumption is very seldom used at the pressure of delivery. This is generally far too high for the lamps or motors employed. The possibility of using high and extremely high pressure is one of the advantages of

A.C. as far as the conveyance of electric power to great distances is concerned, because the higher the pressure the smaller the current strength corresponding to a given amount of power, and the smaller the quantity of metal required in the transmission line. But if high pressure is an economic necessity as regards transmission of power, it is an objection as regards the utilisation of power. We must therefore transform at the place of utilisation the small current of high pressure into a large current of low pressure. This is done by an apparatus called the "transformer." The principle, on which the transformer works, is illustrated in Fig. 22. The high pressure current is delivered at the terminals T_1 T_1. To these is connected a coil of many turns of wire wound on an iron core C. On the same core is placed a second coil of fewer turns of stouter wire, and the consuming devices (lamps or motors) are connected to the terminals T_2 T_2 of this coil. The high-pressure current passing through the winding of the primary coil P, magnetises the iron core, and since the secondary coil C is encircling this core also, it is traversed by the flux of force produced by the primary current. Thus by electromagnetic induction

an e.m.f. is generated in the coil S, and this is the real source of the secondary current supplied to the consuming devices. Fig. 22 is only a diagrammatic representation of a principle, not of the actual apparatus. In reality the two coils are placed much closer together and the iron core has not open ends, but is in the form of a closed magnetic circuit. It may have the shape of a rectangular frame

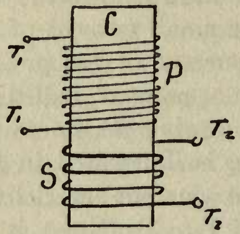

Fig. 22.

built up of thin iron plates, the two longer limbs of the rectangle forming the two cores on which the coils are placed, whilst the shorter traversing limbs act as yokes to complete the magnetic circuit. This type is called a "core transformer." In another type there is only one central core, and the magnetic circuit is closed on both sides by yokes forming each three sides of a rectangle, and thus enclosing the coils on either side

with a kind of iron shell. This type is called a "shell transformer." In either type the primary and secondary coils are placed as close together as is compatible with an efficient insulation between them. This is done in order that the secondary winding may be traversed by as near as possible the whole flux which passes through the primary winding, and thus the ratio of transformation is very nearly equal to the ratio between the number of turns in the two windings.

The efficiency of transformers is remarkably high. Under efficiency must be understood the ratio of the power received by the primary circuit to the power given out by the secondary circuit. No machine can have an efficiency of unity; the output must always be smaller than the input, but the difference in the case of a transformer is much smaller than in the case of a dynamo of equal power. Even a small transformer of but a few KW. power may have as much as 90 per cent. efficiency, whilst large transformers of 1000 KW. may reach 98 or 98½ per cent.

Alternating currents are produced by machines of the type represented by Fig. 15. Such a machine is simply an implement for converting mechanical power into the electric

power represented by the A.C. flowing under the potential difference corresponding to the excitation of the magnetic system. Obviously the converse process must also be possible. If we supply electric power in the shape of an A.C. to the armature of this machine and keep the field-magnets excited as before, we must be able to obtain mechanical power from the shaft. But then the speed must be exactly that corresponding to the frequency of the A.C. supplied. To use a machine of this kind as an electric motor we must first bring it up to speed by some means, and only if the speed is exactly such that the rhythm of the passage of the poles in front of the armature coils synchronises with the frequency of the available supply may we switch this on to the armature. Electric motors of this kind are therefore called "synchronous motors." The necessity of bringing the motor first up to speed before being able to switch the driving current on is an inconvenience which renders such motors unsuitable for general purposes.

To the late Professor Ferraris of Turin belongs the merit of having discovered a principle of alternating current working by which the motor may be started by the alternating

current itself without bringing it first up to the speed of synchronism. Motors of this kind are called "asynchronous" or "non-synchronous" motors. As already stated, Ferraris himself did not realise the enormous technical importance of his discovery, but

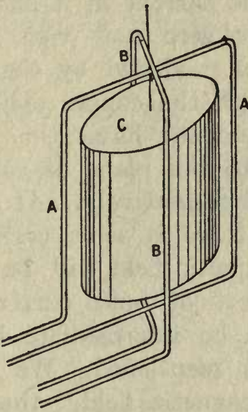

FIG. 23.

this does not detract from the merit of having made it. The classical experiment of Ferraris is illustrated in Fig. 23. A copper cylinder C is suspended within two coils A and B so placed that their planes stand at right angles to each other. For the sake of clearness the illustration shows coils of only one turn each, in reality each coil contains a large number

of turns. Now imagine a machine as shown in Fig. 15 having two independent windings as pointed out on p. 186. Let one winding supply current to the coil A and the other to the coil B. The phases of the two currents are displaced in point of time by a quarter period. If the current in A has crest value that in B is zero and vice versa. The magnetic field produced by these coils and passing through the copper cylinder will at these two moments have the direction at right angles to the plane of coil A and to that of coil B respectively. At intermediate times, when there is some current in both coils, the magnetic field will be due to the combined effect of both currents, and its direction will be intermediate between the two positions mentioned. We thus get a "revolving magnetic field," the number of complete revolutions performed in a second being equal to the frequency. It is as though a physical magnet were whirled round the copper cylinder. The lines of force of this revolving field cut through the metal of the cylinder and thus create induced currents, which in combination with the field produced by the two coils exert a drag on the surface of the cylinder and cause it to rotate in the

same direction. This drag is but a feeble force, but it is easy to augment it by a proper disposition of the parts. In the first place it should be noted that the lines of force are entirely flowing through air, and consequently the induction is weak. If we were to provide an iron path for them, the induction would become

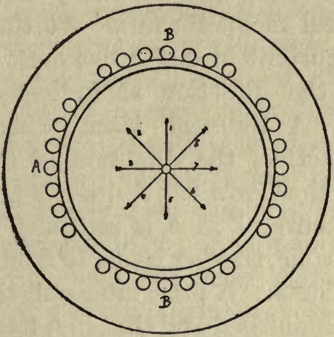

FIG. 24.

immensely stronger. This is the direction in which Ferraris' discovery was developed by various designers. The general principle of improving the magnetic path is shown in Fig. 24.

The coils A and B are embedded in an external iron cylinder, and thus the magnetic reluctance of the external path of the lines of force is reduced to a mere fraction of what it was before. The magnetic reluctance of

the internal part of the path is likewise reduced considerably by making the internal cylinder not entirely of copper, but using an iron cylinder with a mere coating of copper. Thus there is only the narrow space left between the two cylinders where the lines of force have to be forced across a non-magnetic medium, and the result is a very large increase in the total magnetic flux. At the moment that the current in coil A has crest value the flux has the direction as indicated by the arrow 1. A moment later, when B also becomes active, the direction of the flux is shown by the arrow 2. A quarter period later when the current in A is zero and that in B has crest value, the flux is due to B only and has the direction 3. A little later still the current in B has diminished and that in A has grown to some negative value. Thus the flux is turned into the position 4 and so on, the flux gradually passing through the directions given by the arrows 5, 6, 7, 8, and then the cycle begins again.

The motor shown in Fig. 24 has still an imperfection. No definite path is provided for the current induced in the revolving cylinder, technically termed the "rotor." The currents flow more or less irregularly within the whole mass of the metal, and some

of them are therefore not in the most advantageous position for exerting mechanical force. The improvement necessary to overcome this imperfection is obvious. If we replace the copper cylinder forming a coating to the iron core by a regular copper winding embedded in the surface of this core, we constrain the currents to flow along definite paths, which relatively to the currents in the fixed part or "stator" are always in the most efficient position for the production of mechanical force. The modern non-synchronous motor is therefore provided with a winding both on the stator and on the rotor; and both windings are embedded in slots, so that the reluctance of the magnetic circuit is mainly that of the air-gap between the outer surface of the rotor and the inner surface of the stator. This need not be larger than a mere mechanical clearance allowing the inner part to revolve without touching.

A lesser imperfection of the motor shown in Fig. 24 is due to the employment of only two currents. The result of this arrangement is that the strength of the revolving field is subject to certain fluctuations. At the moment that the current in A has crest value the maximum value of the induction in the air-gap

is somewhat less than one-eighth of a period later when both coils are active. The field thus is not only rotating, but also to a slight extent pulsating, and these pulsations give rise to parasitic currents which contribute nothing to the driving force and only waste power. By certain methods of grouping the wires it is possible to reduce these pulsations to a tolerable amount, but a better way still is to build the motor for three-phase current. The combined action of three currents mutually one-third of a period apart in point of time results in the production of a sensibly constant flux revolving at constant speed. A mechanical analogy of the kind of irregularity to be expected in the cases of two-phase and three-phase motors is furnished by deep well pumps. With such pumps it is important that the rate of flow of water in the delivery pipe shall be as uniform as possible, because with a great length of delivery pipe the column of water, alternately accelerated and retarded if the flow is not uniform, throws considerable stresses on the machinery. A pump with one cylinder only is, therefore, even if a large air-vessel is used as equaliser, not so satisfactory as a pump with two cylinders and cranks set at 90 degrees. More

satisfactory still is a pump with three cylinders and cranks set 120 degrees apart. With this arrangement the flow of water is so uniform that the use of an air-vessel as an equalising agent becomes almost superfluous. The two-cylinder pump is the mechanical analogy to the two-phase motor, and the three-cylinder pump is that of the three-phase motor.

Since, as will be shown in the next chapter, the use of three phases has also the advantage of considerable economy in the amount of metal required to carry a given power over a given distance, the use of three-phase current for motive power purposes has become almost universal.

Small asynchronous motors are sometimes made with what is technically known as a "squirrel cage rotor," the name being derived from the peculiar type of winding used. In the ordinary sense of the word the conductors on the rotor do not form a winding of wire, but a series of copper bars laid along and embedded into the surface of the core. At either end the bars are all joined up by metal rings, thus forming a kind of squirrel cage. This construction has the advantage of great mechanical simplicity and strength, but the disadvantage that at starting the motor takes

a large current at a low power factor. At starting the rotor is at rest and only gradually gathers speed. Whilst running slowly the frequency with which the rotor bars are cut by the revolving field is great, and consequently the e.m.f. and the rotor current are also great. A great rotor current means a weakening of the flux originally produced by the stator current, but as this flux is mainly instrumental in balancing the e.m.f. impressed on the stator terminals, and since this e.m.f. is constant, no appreciable weakening can take place. The action of the machine is that it automatically admits more current through the stator to make up for the weakening effect produced by the excessive rotor current at starting. A sudden rush of current taken from the supply terminals is disturbing to the rest of the machinery supplied from the same system, and hence the use of squirrel-cage motors must in the interest of all consumers be restricted to small types. When motors of large power are required it is necessary to limit the excessive rush of current at starting, and this is done by using a rotor with proper winding, the terminals of which are connected to slip-rings on the shaft. On these slip-rings are placed brushes which are

connected with a starting resistance. As the motor gathers speed this resistance is gradually short-circuited. Thus at no time is there any excessive rush of current in the primary or stator winding. When the motor has attained full speed the whole of the starting resistance is cut out and the slip-rings are short-circuited. In this condition the speed at which the rotor winding is cut by the revolving field is only a few per cent. of the speed at starting. It is the difference between the speed of the revolving field and the speed of the rotor. This is technically termed the "slip" of the motor, and varies from about 6 per cent. in small motors to 2 per cent. in large motors. The heavier the mechanical load on the motor, the greater is the slip. A motor of 50 H.P. would have about 1½ per cent. slip at half load and about 3 per cent. at full load, so that practically, although it is non-synchronous, the speed may be considered as approximately constant. This constancy of speed under variable load is a desirable feature in most of the industrial uses of motive power, and together with the great simplicity of mechanical construction explains why these motors, originally grown out of a scientific discovery made by a professor of physics, have become so popular.

CHAPTER IX

THE DISTRIBUTION OF ELECTRICITY

As a mere theoretical proposition, the transfer of electric power from the battery or machine in which it is generated to the lamp or other apparatus in which it is to be utilised is quite a simple affair. A few wires insulated from earth and from each other and a switch is all that is required. But if we come to the practical proposition of distributing electricity for general use, this seemingly so simple problem assumes a very formidable aspect. The connecting wires become heavy conductors many miles long, they may have hundreds of ramifications to reach as many users of electricity, the efficient insulation of the electric mains with all their branches requires special care, and the switches may become so large that they cannot any longer be worked by hand, but require special electric motors to close or open them. There is further the necessity, on the one hand, of

protecting the user and the public from accidental contact with any charged conductor, and on the other the necessity of protecting the distributing plant itself from injury by external forces, including atmospheric electricity. Thus it comes that in modern works for the generation and distribution of electricity the distributing plant is an important item financially, its cost ranging from about a quarter to one-half of the total capital outlay.

The supply of electricity in urban areas must necessarily be by means of cables laid underground, and the cost of these cables is one of the principal items in the cost of the distributing plant. The higher the pressure at which the current is conveyed the smaller may be the cross section of the cable, but where the supply is for general purposes, including domestic lighting, there is a limit to the pressure. Incandescent lamps of moderate candle-power cannot be made for a higher pressure than 250 volts, and even this is exceptional. The general voltage is 220, so that a supply to be generally used must be given at about that pressure.

The current in passing from the place of generation to the place of use has to pass

along wires, and part of the voltage is lost in overcoming the ohmic resistance of these wires. This loss of pressure varies directly with the current. At the time that the greatest number of lamps in any particular district are switched on, the loss of pressure in the cables supplying that district is greatest, and in order that the lamps may still burn with normal brightness, the pressure at the home end of the distributing system must be raised to a value just sufficient to make up for the loss of pressure due to ohmic resistance. But an exact adjustment is impossible; some lamps are nearer and some farther away from the home end of the cable. The current when it reaches the nearer lamps has not lost quite as much of its voltage as when it reaches the farther lamps. To make the delivery voltage absolutely right for every lamp is obviously impossible, but we can approach this ideal condition by the adoption of the following principles: First use cables stout enough so as to limit the total loss of pressure to a moderate amount, say 10 to 15 per cent. of the lamp voltage; secondly, divide the distributing plant into two distinct portions, namely "feeders" and "mains."

To explain what is meant by these terms,

and why by the adoption of a particular method of using the conductors a satisfactory service to all customers of an electricity works can be given, let us take by way of example the service of electricity to the householders along a street a mile long, the electricity works being at one end of this street. Here we have some customers quite close to the place of generation and others a mile away. If we were simply to connect the home end of these cables with the machines and supply the whole of the street from this one end only, we should get so great a variation in the voltage in different houses as to make the supply very unsatisfactory. The customers close by would get far too high a voltage and their lamps would be destroyed by "over-running," and the customers at the other end of the street would get hardly any light. The variation of delivery voltage legally permitted to public supply companies by the Board of Trade regulations is plus or minus 4 per cent., but even this seemingly moderate variation would be intolerable to the user of electric light if it occurred suddenly. The light given by an incandescent lamp varies at a much greater ratio than the voltage, about four to six times as much, so

that a 2 per cent. voltage variation means about 10 per cent. light variation. The human eye has so great a power of adaptation to changes in illumination that a 10 per cent. variation, if it takes place very gradually, will scarcely be noticed, certainly less than the illumination of a room by daylight if clouds are passing over the sun.

If a current were fed into our street main of a mile in length at one end only, the voltage difference between the two ends and at different times would be very much greater than 2 or even the 4 per cent. allowed by the Board of Trade, and no power of adaptation of the human eye could make such a service acceptable. To put at the near end lamps of higher and at the far end lamps of lower voltage is no remedy. At the time of small demand, say early in the morning, there will be very little difference in the voltage all along the street, so that the lamps at the far end would be over-run and soon burn out. At times of great general demand, the so-called "peak-time," the difference in voltage would be very great. By grading the voltage of the lamps according to distance from the central station we can only slightly mitigate the evil, but certainly not cure it. The exact

hour when the peak in the lighting load occurs depends on the kind of premises lighted. In offices it is between five and six; in residential districts between seven and eight, because at that time the kitchen premises are fully lighted, the bedrooms are used by people dressing for dinner, and at the same time the reception-rooms must be lighted up. Whatever the property lighted, there is a great variation in the demand for current at different times of the day, and the cables must be designed to be equal to the maximum demand that may occur.

If the street main is fed at the home end, the total current sent into it at that end is proportional to its length. The resistance is also proportional to its length, and since the drop is proportional to the product of current and resistance, we find that for a given density of supply expressed at so many amperes per yard run, the voltage drop is proportional to the square of the length. If, then, instead of feeding the street main at one end, we feed it in the middle only, we substitute two half-mile lengths for the single mile and we quarter the voltage drop. To do this we require a separate cable, the so-called "feeder," from which no current is taken

on the way. This merely serves to bring the current into the middle of the main where the feeder is tapped into it. We can still go a step further and arrange for feeding points closer together, so as to reduce still further the length of each section of main in which the voltage drop takes place. This drop may thus be made exceedingly small, even at peak-time, but then we must make such arrangements as will result in a constant voltage at all the feeding points. All the mains in the streets of a town are arranged to form a connected network, and at certain points of this network, preferably those close to districts of great demand, the network is tapped by feeders. Obviously these feeders are not of equal length or equal resistance, and they will certainly not carry equal currents at all times of the day. It becomes, therefore, necessary to adjust the voltage impressed on each feeder or group of feeders at the central station independently, and that is done by the use of so-called "boosting dynamos." These are small machines, which may be regulated so as to raise the voltage at the home end of each feeder by just the amount necessary for making up what at any time is lost by ohmic resistance in that feeder.

By using an interconnected network, numerous feeding points, boosted feeders, and generally cables of ample cross section, it is thus possible to give a perfectly satisfactory service with a lamp voltage of 220 V. There remains, however, the question whether such a distributing system can be laid down at a reasonable cost? In most cases the answer is in the negative. With the low pressure of 220 volts the amount of copper required for feeders and mains would represent a prohibitive outlay. There is only one way in which we can economise copper, and that is by raising the pressure. Suppose we could get lamps which will work satisfactorily with double the pressure, or 440 volts, then for the same power we should only have to transmit half the current. If we also halve the cross sections of all cables we should have the same absolute voltage drop as before, but as the pressure is doubled, this means half the percentage drop. To get the same percentage drop as before we may again halve the cross section of all the cables, that is to say, by doubling the pressure the whole system will only require one quarter the amount of copper as before. This brings us into the region of the commercial possibility

of a general supply of electricity to householders. But lamps for 440 volts are not obtainable. To use a supply at 440 volts with the lamps at present on the market, we should have to use two in series connection, that is to say, always burn lamps in pairs. This would be an intolerable restriction to which no householder would submit. Now suppose for a moment that we do not put two neighbouring lamps in series, but two neighbouring houses. This means that a tapping from the positive main only is taken to supply house No. 20, and a tapping from the negative main only to supply house No. 21, the circuit being completed by a wire taken from the lamps of No. 20 to those of No. 21. If both householders were to agree that they would at all times burn exactly the same number of lamps, we should have electrically the same condition as in the previous case, where we arranged the lamps in one house in pairs.

This arrangement would, however, be still more intolerable than the previous one. Now suppose that we put all the houses of even numbers on the positive main and all the houses of odd numbers on the negative; further, that all the connecting wires between the houses are replaced by a third main, then

we get a system under which each house having an even number would be connected to the positive main and this third main, and each house having an odd number would be connected between the negative and the third main. The condition that there shall be the same number of lamps in use on the positive and the negative side of this third main will be almost naturally fulfilled, and there will be no need of asking householders to agree with their neighbours as to the number of lamps each shall burn at any given hour. With a sufficiently large number of houses connected to this three-wire main there will, by the law of averages, be an almost equal demand at all times on the positive and negative main, and the current which flows in the third or middle wire will be very small.

This is the principle of the "three-wire system" of distribution of electricity invented simultaneously by Mr. Edison and the late Dr. Hopkinson. It is now the system generally used in public electricity supply. The middle wire has to be connected to corresponding feeders and thus brought back to the central station, where some apparatus for the division of the voltage between the outer wires must be provided. In stations

using a secondary battery the division of the voltage can easily be made by bringing the middle wire to the centre of the battery; or a so-called " balancing set " may be provided, consisting of two dynamos coupled in series and connected across the outer wires. These are small idle-running machines whose sole office is to divide the total voltage into two equal components. The middle wire is attached to the connection between the two dynamos. These dynamos may be quite small, since the out-of-balance current brought to them by the middle wire is only a very small fraction of the total current supplied to the outer wires; generally only a few per cent. It suffices, therefore, to give the middle wire about half the cross section of one of the outer wires, both in the feeders and in the distributing mains. By using the three-wire system the total amount of copper required for the supply of electricity throughout a given district is thus reduced to about 32 per cent. of the amount that would be required for the same service at the same lamp voltage with a two-wire system.

This relation holds good whether the supply is that of a continuous or that of an alternating current. In the latter case there is sometimes

a further possibility for economy in copper by the use of balancing transformers. In the orthodox method of working the three-wire system the feeders as well as the mains are provided with the third wire. It is necessary to carry the third feeder wire back to the central station, because it is at the central station where the division of voltage into the positive and negative part of the system is made. With continuous current this is necessarily so, because the subdivision of the voltage requires either a storage battery or machinery in motion. If the supply is by alternating current, then the subdivision of voltage can be made by an apparatus which is not in motion and requires no supervision. This apparatus need, therefore, not be placed in the central station where the feeder starts, but at the feeding point or near it on the mains where the feeder ends. The third wires need then only be provided for the mains, but may be omitted from the feeders. The apparatus for the subdivision of the voltage between the two outer wires of the main is simply a transformer with an equal number of turns in its primary and secondary coil. Both coils must in reality be considered as the two halves of one single coil; the middle point is

connected to the third wire, whilst the terminals are attached to the two outside wires. Such a transformer is technically termed an "auto-transformer," and where the ratio of the windings is as 1 to 1, it simply serves to halve the total voltage and allow whatever out of balance current may flow in the middle wire to find its way back to the outer wires.

By the means here described it is possible to give a satisfactory service of electricity over a district extending for about a mile all round the central station. The term "central station" is derived from the fact that in the early days of the public supply of electricity the works where the current was generated were placed as near the centre of the district of supply as was found possible. Now-a-days it is not a correct term. The tendency is to put the works eccentrically to the supply area; and this for obvious reasons. In the central part of the town, where there is the greatest demand for current, land is too valuable to be occupied by a works, there is the difficulty of bringing coal to the works, taking the ashes away, and there is the further difficulty of obtaining an abundant water supply for condensing purposes. It is true that if the water supply is restricted cooling

towers may be used, but then there is the probability that these, by giving off steam, will prove a public nuisance. The noise and vibration inseparable from the use of powerful machinery have also to be taken into consideration, so that on the whole a central position for the electricity works becomes impossible. If we still speak of a central station, the term must not be used in a topographical sense, but rather as indicating that in those works the generation of electricity required over an extended area has been centralised.

But if we place the station outside the boundary of the town it is no longer commercially possible to supply the district with current at the moderate pressure of 440 or 500 volts. The feeders are necessarily long and their resistance is high. To get an efficient transmission system we must raise the pressure to a very much higher value, far above that which is suitable for the lamps. This leads to the establishment of so-called "sub-stations" within the supply area. These sub-stations receive high-pressure current from the central station outside of the town, and convert it to such a pressure as renders the current directly applicable. Thus the

sub-stations become topographically central stations for a limited area. The objections to central stations mentioned above do not apply to sub-stations. They use neither coal nor water, they need not necessarily contain moving machinery, and if such machinery is erected in a sub-station it is of purely rotative type, such as electric motors and generators, which work without causing any noise or vibration; and finally the amount of space required is very small, so that the cost of land, even in the middle of the town, is no longer prohibitive. Where the supply is by alternating current no land at all is required. The converting apparatus consists mainly of transformers which may be put either under the pavement or in kiosks at street corners.

If a continuous current supply must be given to the householders, then there must be in the sub-station not only a conversion as to voltage, but also as to type of current. The conveyance of electric power from the central station to the sub-station is done most economically by means of three-phase current. This current is used to drive machinery which produces continuous current. Such an arrangement is shown diagrammatically in

Fig. 25. M is a three-phase motor driven by the high-pressure current coming from the central station. G is an ordinary D.C. generator directly coupled to the motor. The sub-station may be provided with a number of such units, storage batteries may be used, and the whole service is carried on exactly as in a D.C. central station, the only

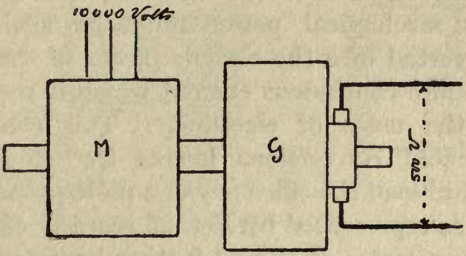

FIG. 25.

difference being that there are no boilers, engines, chimney, condensing plant, coal bunkers or ashpit, and no danger of the works becoming a nuisance to the neighbourhood. All the plant which in the main station is required for the generation of power is here represented by electric motors. The space occupied is quite small and the service exceedingly simple. In so far as simplicity of operation goes the system is admirable;

it has, however, some minor defects. The whole of the power has to undergo a double conversion. In the central station the mechanical power of the steam engines must be converted into the electrical power represented by the three-phase high-pressure current; this at the sub-station has again to be converted into mechanical power by means of the electric motors, and, finally, this mechanical power must be again reconverted into the electric power of the low-pressure continuous current which is supplied to the users of electricity. This chain of repeated conversions lowers the efficiency. At full load the efficiency of a motor generator set as represented by Fig. 25 scarcely exceeds 83 per cent. It should further be noted that for every kw. capacity in the D.C. side of the set, about 1·2 kw. capacity must be provided in the A.C. side, so that the total dynamo capacity in the sub-station must be more than twice the output capacity. This makes the system expensive in capital outlay, whilst the low efficiency makes it expensive in working.

Both these defects are to a large extent overcome by the use of so-called "rotary converters," illustrated diagrammatically in

Fig. 26. Here, instead of using two distinct machines, namely a motor and a generator, only one machine is used, which fulfils both functions at once. This machine, moreover, is smaller than either M or G of Fig. 25, so that the capital outlay is considerably reduced. The converter C is an ordinary D.C. machine with the addition of suitable

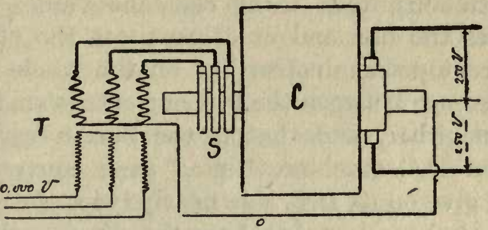

FIG. 26.

connections by which alternating current can be supplied to the same armature from which the continuous current is taken. The wires on the armature are thus simultaneously traversed by the alternating current which drives the machine and by the continuous current which is generated in the machine by reason of its being driven. Without going minutely into the somewhat complicated theory of the action of this type of machine, it will be clear that by Lenz's law the direction

of the current which produces motion must on the whole be opposed to the direction of the current produced by this motion. Thus in each armature wire the A.C. and D.C. flowing simultaneously neutralise each other to some extent. This neutralisation can obviously not be absolute, for one current is alternating, that is continually changing, and the other is continuous, that is of constant value. At times the one and at other times the other current predominates, but on the whole the difference between the two currents is smaller than either, and that is the reason why a given D.C. machine, if used as a converter, will give on its D.C. side nearly twice the output that can be taken from the same machine if worked as an ordinary D.C. generator.

The connections for the supply of the A.C. are tappings of the armature winding brought out to so-called " slip rings " S on which brushes bear. Since the same armature winding serves both the A.C. and the D.C. side of the machine, and since the e.m.f. induced in both is produced by the wires of the armature cutting through the same magnetic flux, it will be obvious that there must be a definite relation between the e.m.f. of the alternating and that of the continuous

current. The ratio between the two e.m.f.'s varies a little with the constructive details, but may be taken as about 2 to 3, so that if 500 volts is required at the D.C. side, an A.C. of about 330 volts must be supplied to the slip rings. Obviously this is far too low a pressure for economic transmission of electric power from the central station. To carry the thousands of kw. required for the supply of a town from the central station to the sub-stations by means of cables of moderate size and cost, we require pressures of 10,000 volts or more, so that the use of a transformer, T, becomes necessary. The use of this transformer has the incidental advantage that we obtain an easy and inexpensive way of subdividing the pressure between the outer wire if the distribution on the D.C. side is to be made on the three-wire system. We need only attach the zero, or middle wire *o*, to the electrical centre of the secondary winding of the transformer as shown.

The efficiency of a converter set, including the transformer, is sensibly higher than that of a motor generator set. It generally reaches 92 per cent. In another respect the converter has also an advantage over the

motor generator. Since the motor is of the non-synchronous type, its power factor must be less than unity. This means that the feeder coming from the central station has to carry rather more current than corresponds to the actual energy transmitted. This extra amount of current brings no power; it only heats the feeder and lowers the efficiency of transmission. It also makes it necessary to make the A.C. generators at the central station rather larger than would be the case if these machines were called upon to give only the useful component of the current. A power factor less than unity at the delivery end of the feeders means, therefore, not only stouter and more expensive cables, but also somewhat more expensive plant at the central station. This drawback of the motor generator does not obtain in sub-stations where converters are used. The converter, as far as the A.C. side is concerned, is a synchronous motor, and in such a machine it is always possible to so adjust the excitation that the armature will take the A.C. exactly co-phasal with the alternating e.m.f. It is thus always possible to work with a power factor equal to unity, and the current delivered by the generators at the central station has no idle,

or so-called "wattless" component. Its absolute value is therefore exactly commensurate with the power it actually transmits. The cables need not be stouter than corresponds to the power they actually deliver, and the generators need not be made larger than corresponds to the actual power developed by their engines. Since a rotary converter is a synchronous machine, it must be first run up to speed before being switched on to the A.C. side. This may be done by a small non-synchronous starting motor mounted on the shaft of the converter, or, if batteries are used at the sub-station, the converter may be run up to speed by D.C. derived from the batteries.

A very important application of rotary converters is in connection with electric tramways and railways working with continuous current. The working D.C. voltage of tramways is about 500 V., that of railways is generally a little higher: in Europe 600 to 750, and in some cases 1000 V. In America some lines are worked at 1200 V., and one in England is now being equipped for 3500 volts; but even at this pressure, the direct supply of D.C. from the generating station to the trolley wire would require so great an

expenditure of copper for feeders as to make the system commercially impossible on any but fairly short lines. It thus becomes necessary to transmit electricity from the power-house at high pressure to sub-stations placed at intervals along the line, and to convert the three-phase high-pressure current at these sub-stations into continuous current, which is supplied by means of feeders to the trolley line. The apparatus used is of the type shown in Fig. 26, with this difference, that the middle wire *o* on the D.C. side is omitted and that the negative brush is connected to the rails or by way of a switch-board to the negative return feeders bringing the current back from the rails, whilst the positive brush is connected with an omnibus bar on the main switch-board from which all the feeders start.

The current taken by electric tramways and railways is very fluctuating. In the case of tramways the fluctuations are the less felt the larger the system, that is to say, the greater the number of cars drawing current from a particular power-house or sub-station. If only a small number of cars is on the system the fluctuations may become very great. This is especially the case if a block in the

traffic occurs, and on the street being freed from the block all the cars in that street start at once. In electric railways the fluctuations are even greater than on tramways, because there are not so many motors simultaneously in use whose demand for current may, as in very large tramway systems, more or less average out to a fairly steady load. The generators in a traction station are thus subjected to great and quick changes of load. To mitigate the excessive stresses brought on to the generating plant by these violent fluctuations of load, storage batteries may be used which act as a kind of reservoir of energy, taking in a charging current at the times that the line requires less than a certain amount of current, and giving a discharge current and thus helping the engines at the time that the demand for current on the line becomes excessive. The storage battery acts as a sort of elastic buffer between the power-house and the trains, and it is therefore called a "buffer battery." The buffer battery may be used either in the main power-house or in the sub-station; in either case its advantages are that the generating machinery may be reduced in size. It has not to be large enough for the occasional and excessive demand, but only

a little larger than corresponds to the average demand. There is the further advantage that the engines are worked at a steady load, and therefore with a maximum of efficiency.

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